MOISTURE TRANSFER IN A POROUS, HYGROSCOPIC SOLID

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Preface

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CHAPTER I

INTRODUCTION

Background

A method long used for curing peanuts in the United States was the stackpole. By the early 1940's, it was evident that the high labor requirement associated with the stackpole method was no longer tolerable to the producer. On farms with tractor power the use of the stackpole method accounted for one-third of the total man hours used in producing peanuts (20).

The search began for better ways in which to accomplish the curing task. Many growers discontinued stacking in favor of windrowing the peanuts. Windrowing reduced labor requirements (2) (41). Except under adverse weather conditions, windrow curing resulted in peanuts comparable in quality to those cured with the stackpole method. Teter reported that conditions of temperature, humidity, and rainfall made windrow curing impractical in some peanut growing areas of Virginia (44). In the Southeast and Southwest, peanuts in the windrow might frequently need to be shaded from direct sunlight to prevent impairment of quality due to high temperatures (45).

Up until about 1945, it was apparently the belief of most people in the peanut industry, that peanuts had to be cured on the plant (2).

Some contended that vital elements were transferred to the peanut from the plant during the curing process. For this reason, preliminary artificial curing tests were conducted with the peanuts attached to the parent plant. The principal disadvantage of this method was the necessity of extra facilities to handle the bulky plants.

In the interest of eliminating the handling of the plants, Bailey and others cured peanuts in naturally ventilated rooms (2). They consistently found that neither differing amounts of the plant detached from the peanuts nor the time of detachment affected quality during curing.

Sorenson (41) reported the use of heated air in the artificial curing of peanuts in 1946. The results appeared to be satisfactory, but a complete analysis of quality was not made. In Georgia, artificial curing in bulk bins or artificial bulk curing with air temperatures below 100°F produced no detrimental effects from a physiological standpoint (13). In addition, investigations with a small laboratory unit revealed that a correlation existed between shelling characteristics and rate of air movement, air temperature, and initial and final moisture content of peanuts. Similar observations were made in Virginia about 1950 (1).

Other experimental studies in Georgia prior to 1950 suggested that the curing of peanuts could be achieved by artificial means and/or by windrowing (14). Some of the first artificial curing tests in which the flavor aspect of quality was analyzed, were conducted in

Florida and Georgia (32) (3). Air temperatures as high as 115°F were used before off-flavor was noted. High rates of moisture removal resulted in bland flavor, testa looseness and kernel breakage. Curing temperature did not affect the degree of testa looseness or kernel breakage. These findings were confirmed by other investigators (5).

Baker and Cannon (4) reported that peanuts subjected to air temperatures above 100°F would develop an off-flavor. Best results were obtained by using air temperatures of 85°F to 95°F and air flows of 45 to 60 fpm. The rate at which peanuts lost moisture was not uniform from top to bottom in a bulk bin setup. The latter observation was also made by Beasley and Dickens (5). In fact, earlier investigators had recognized this problem and had recommended a reversible air flow system to lessen the degree of nonuniform curing (14).

The results reported by Teter (44) in 1954 agreed, in general, with those of Baker and Cannon. Peanuts that were artificially bulk cured in less than 96 hours, or at air temperatures above 85°F to 95°F, or at air flows greater than 13 to 17 cfm./ft.^{3} of peanuts, might be expected to produce a product of lower palatability. Teter recommended leaving peanuts in the windrow for five to six days after which curing would be completed artificially with 80°F to 90°F air flowing at 10 to to 20 cfm./ft.^{3} of peanuts. He implied that no practical artificial curing method for a freshly dug, Virginia-type peanut was known.

Evaluation of studies by Teter and Givens (47) in 1957 showed the same curing recommendation as stated above. Curing too slowly resulted

in mold growths in the peanuts.

In the many artificial curing studies that were conducted on peanuts prior to 1957, bland flavor was often associated with rapid curing rates. The absence of an explanation for the apparent association caused investigators to speculate on the cause of bland flavors. Pickett (34) postulated that a minimum time was required in which reactions in the peanut could take place in order to avoid a disruption of a normal metabolic sequence. Contrary to the postulation, a satisfactory product was obtained when he cured peanuts in a vacuum at room temperature in 16 hours. An additional complication arose from the fact that peanuts freeze-dried at about -80°F, whereby all enzyme action should have been negligible, always resulted in bland flavor.

Teter (45) indicated that after a peanut had ceased to synthesize food, a ripening process before curing was important in preventing the development of a bland flavor during the curing process. However, the research efforts of Beasley and Dickens (5) did not substantiate this theory.

Off-flavor in peanuts has been consistently associated with high curing temperatures, but how they are related is not known. Efforts to relate the two by abrupt or significant chemical changes in the peanut have not been successful (35). Dickens (11) suggested the hypothesis that anaerobic respiration of the peanut at high curing temperatures was a possible cause of off-flavors. Extensive studies

on this hypothesis have been conducted by Schenk (37) (38) (39). He reported that the gas exchange rate of peanut kernels is inversely related to the curing temperature. Between temperatures of 25°C and 82°C, a case-hardened layer was formed at or near the surface of the peanut kernel. This layer was found not to appreciably affect the rate of moisture movement, but did affect the movement of other gases. Further evidence was obtained which showed that anaerobic respiration did occur under the curing conditions which produce off-flavor.

Curing studies since 1960 have supplied additional information. Attempts by Beasley and Dickens (5) to relate bland flavor with a particular feature of the harvesting or curing process have been unsuccessful. They showed that the subjective method of taste panels used by all investigators to appraise peanut flavor could be contradictory. Cecil (9) found that the degree of hardness or toughness of a peanut kernel was not associated with artificial curing treatments involving air temperatures from 70°F to 140°F. His rapid curing tests by artificial means produced contradictory results. In 1961, high percentage shelling damage was correlated with a high rate of curing. However, low percentage shelling damage was associated with a high curing rate in 1962.

Importance of Study

The 1962 peanut crop in the United States was estimated to be 1,811 million pounds of whole peanuts (10). In the production of a

peanut crop, growers try to deliver excellent quality raw peanuts to the processor, who has the responsibility of maintaining peanut quality and flavor.

Continued consumer acceptance of raw and processed peanuts depends on many attributes of quality. Those attributes most commonly associated with the curing process are shelling properties, flavor, and aroma.

Loose testa and broken kernels are undesirable in peanuts. Removal of the testa during shelling often results in the kernel becoming soiled. In the blanching process, loose pieces of testa often adhere to the kernel and result in undesirable appearance of the kernel. This appearance and the presence of the broken kernel do not appeal to the consumer.

Overdrying is undesirable because it drastically increases shelling damage. Beasley and Dickens reported that a decrease from 9.8 to 6.1 percent in moisture content corresponded to an increase in shelling damage from 2 to 8 percent (5). Restoring the moisture to its original level reduced the shelling damage to two percent. When low humidities and high temperatures are used in artificial curing, overdrying occurs where the drying air enters the mass of peanuts. Baker and others (4) indicated the need for continuous unloading at the bottom of the bin due to faster drying at that level. Butt (8) reported that quite a differential in moisture content can exist in a lot of peanuts only 18 inches deep when cured artificially.

This observation indicates nonselective control within the bulk, allowing peanuts at various depths in a bin to experience different curing conditions.

The rate at which moisture is released from the peanut is another factor influencing the amount of shelling damage. As early as 1950 reports showed that the two were proportional (3) (4). The existence of this relation restricts the capacity of a bulk curing installation if shelling damage is to be minimized. This restriction arises because of nonuniform rates of drying within the bulk, thereby lengthening the duration of the curing process as a result of low drying rates in localized regions.

Unacceptable flavors are of two types. The one of higher intensity is off-flavor, which is bitter. The other is bland flavor or the lack of capacity to develop peanut flavor.

There seems to be general agreement that off-flavor in peanuts can be expected in curing if air temperatures in excess of 100°F are used. Similarly, bland flavor is associated with the rapid rate of moisture removal. However, the low intensity of this flavor characteristic has caused difficulty in obtaining reproducible results relating bland flavor to any one factor (5).

Formation of the above mentioned flavors can be avoided in artificial bulk curing only through careful management. As for windrow curing, peanuts are frequently heated to a high temperature by direct sunlight. This temperature has been known to reach 131°F and

to lower quality (3).

Other disadvantages are also inherent in the present methods of curing. Windrowing puts the peanut grower at the mercy of the weather. Up to half the peanut crop can be lost if peanuts are windrowed immediately prior to a long period of inclement weather (30). Losses are due both to quality deterioration and physical loss of stack peanuts.

Many peanut growers initiate curing in the windrow for a few days, then finish the process artificially. This combination eliminates much of the expense of artificial curing, yet it avoids some of the weather hazards. In certain peanut producing areas, however, Teter reported that this combination did not seem economically practical due to excessive overhead expenses (46). He indicated that the expense could be reduced by increasing the artificial curing capacity, which implies an increased curing rate.

Statement of Problem

Over much of the moisture content range encountered in curing, a freshly-dug peanut kernel will shrink as a result of water removal. In the process of water removal, the outermost layers of the kernel are the driest, establishing a moisture gradient. The outer layers tend to shrink the most, causing tensile stresses parallel to the surface. These stresses in the outer layers increase with the moisture gradient. Breakage or rupture of the kernel results if the magnitude

of the moisture gradient is such that the ultimate strength of the outer layers is exceeded. Thus, greater moisture removal rates by artificial bulk curing produce increased moisture gradients and increased kernel breakage.

Dielectric heating was proposed as a different technique by which peanuts might be cured. One prerequisite for investigating the application of dielectric heating is a study of the electrical properties of the material. Some electrical properties of peanuts have been measured by the author (48). Although a dielectric heating study normally follows an electrical properties investigation, the author believed that another fundamental problem should be considered.

Dielectric heating has the unique ability of adding heat internally. This offers a possible means of controlling the moisture gradient for given moisture removal rates in the peanut kernel during the curing process. Because of heat losses, the temperature at the center of the kernel will be the highest. This is contrasted to conventional means of applying heat in which case the center temperature is the lowest. The temperature gradient in a dielectrically heated material favors a moisture driving potential towards the surface since water vapor pressure increases with temperature. The moisture removal rate can be increased with the use of this driving potential. However, the benefits of the potential cannot be fully employed unless simultaneous use of the potential can be made to decrease the moisture gradient. Therefore, the influence of a

temperature gradient as a moisture driving potential should be investigated as a means of controlling the moisture gradient during the curing process.

Objectives of the Study

1. Determine the effects of a temperature gradient on moisture transfer in porous, hygroscopic solids.
2. Determine the temperature gradients that would exist in a peanut kernel during curing using dielectric and conventional heating.
3. Determine the significance of the temperature gradient in controlling the moisture gradient during the curing process in a model representing the peanut kernel.

Limitations

The following limitations were imposed on the study:

1. Corn meal was used as the model packing.
2. Temperatures used in the experiments ranged between 60 and 100°F.
3. Relative humidities of the drying air in the experiments ranged between 24 and 70%.
4. Maximum drying time was 48 hours.
5. Initial moisture contents (dry basis) of corn meal ranged between 25.4 and 36.3%.

6. Bulk density of corn meal packing was 24 lbs. dry meal/ft.^{3}
7. Pore space occupied 66% of the bulk volume of the corn meal packing as determined by an air pycnometer.
8. The majority of the drying tests were replicated only once.

Procedure

1. A theoretical analysis was made on the effect of a temperature gradient on moisture transfer in porous, hygroscopic solids.
2. Assumptions were made as to the heat transfer resistances of the peanut kernel. The temperature gradient in the kernel was calculated assuming the maximum tolerable temperature at the center of the kernel and air temperatures in accordance with accepted environmental curing conditions.
3. (A) A one-dimensional model was constructed with a material having comparable properties of the peanut kernel. The model was of sufficient size to make temperature and moisture distribution measurements as the moisture was removed. Dielectric or internal heating and conventional methods of heating were simulated with a heat source and heat sink at either ends of the model.

   (B) Indirect methods of measuring the moisture distribution were calibrated with a direct method of moisture distribution measurement. A direct method of measuring

moisture distribution was used because the indirect method failed to provide the desired accuracy.

(C) The moisture distributions and water losses of the models were measured under conditions of different temperature gradients, relative humidities, initial moisture contents, and elapsed drying times.

(D) A reduction in the slope of the moisture gradient was interpreted as a reduction of the stresses resulting from shrinkage associated with moisture removal.

CHAPTER II

REVIEW OF LITERATURE

Most of the research related to moisture transfer in porous solids due to a temperature gradient has been conducted using soils. The interest in this research has been a result of anticipated moisture movement in soil due to daily cyclic heating and cooling of the earth's surface.

One of the first investigators, Bouyoucos (7), conducted tests on moisture movement in soils by subjecting one-half of a sealed horizontal soil column to hot temperatures (20 to 40°C) and the other half to a cold temperature (0°C) for 8 hours. With a presumed uniform initial moisture distribution and a continuous soil column, moisture was transferred from the hot to the cold region. He hypothesized this movement to be the result of liquid flow due to increasing surface tension and capillary forces with decreasing temperature. This hypothesis was supported by observations made on subsequent tests in which the hot and cold ends of the soil column were separated by a vapor gap. In this way, a discontinuous soil column was formed. He found the transfer of moisture from hot to cold regions was virtually non-existent.

In the continuous soil column, the transfer of moisture with the 20°C - 0°C end temperature conditions was only one-third that transferred

with the 40°C - 20°C end temperature conditions. The quantity of moisture transferred was minimal at low and high moisture contents, and reached a maximum at an intermediate or a "thermal critical" moisture content.

In other tests with nonuniform initial moisture distributions, he observed the movement of moisture from a moist and hot region to a dry and cold region of soil. In comparison, there was little or no moisture movement from a moist and cold region to a dry and warm region of soil.

In 1943, Smith (40) found that moisture movement was an important consideration in making thermal conductivity measurements on moist soils. In his studies, sealed soil samples at different moisture contents were subjected to temperature gradients of 1 to 6°C per cm. From his observations, he concluded that moisture was transferred from the hot to cold regions of soil by vapor diffusion and possibly convection. The mechanism of transfer appeared to be vapor condensation at the contact points of soil grains. The vapor condensation, in turn, induced capillary movement. This is contrasted with Bouyoucos' hypothesis that temperature effects on capillary forces caused only liquid movement. However, Smith confirmed Bouyoucos' finding that maximum moisture transfer occurs at some "thermal critical" moisture content of the soil.

Investigations before 1950 had repeatedly confirmed the movement of moisture due to a temperature gradient. However, the contradiction that most frequently appeared in the conclusions of these investigations

concerned the mechanism of moisture transfer. The two principal hypotheses were that water was transferred either in the liquid or the vapor phase.

In 1952, Gurr and others (15) reported results on the mechanism of water movement in soils due to temperature gradients. Soil samples were placed in sealed cylinders. Initial soil moisture contents were uniform and ranged between 1.7 and 24.5%. A temperature gradient of approximately 1.6°C per cm. was induced along the axis of the cylinder. A small amount of soluble salt was added to the soil water to detect the transfer of water in the liquid phase. It was assumed that movements of soluble salts were due to transport in the liquid phase only.

After 5 days, the distribution of water and soluble salts was analyzed. The wettest and driest soils showed no transfer of water or soluble salts. For soils at intermediate moisture contents, there was a net transfer of water to the cold end and of soluble salts to the hot end. Figs. 1A, 1B, and 1C show the final distributions of water and soluble salts for loam soil at initial moisture contents of 1.7, 9.6, and 24.5%, respectively.

The net transfer of water to the cold end was explained by the increase of water vapor pressure or vapor driving potential with temperature. In fact, water vapor transfer was assumed to occur under conditions of constant hydrostatic pressure or liquid driving potential. The movement of salt to the hot end indicated a similar movement of water in the liquid phase.

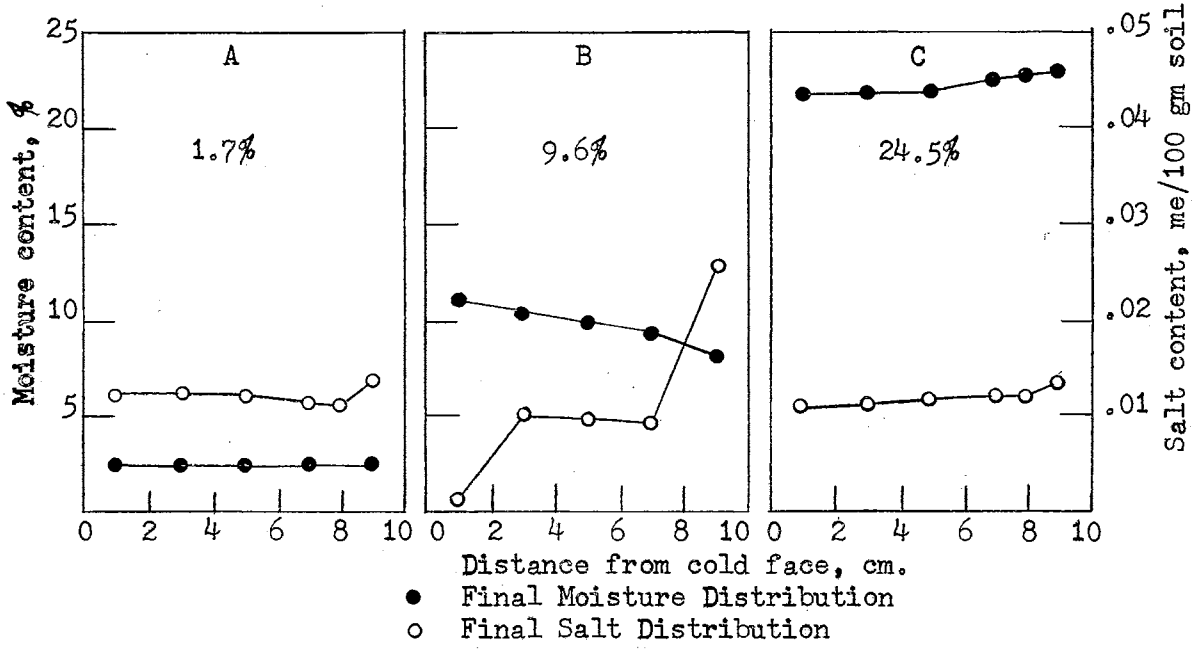

Fig. 1. Distributions of Moisture and Salts in Columns of Loam Soil of Varying Initial Moisture Contents and Subjected to a Temperature Gradient for 5 Days.

The changes in pressures to promote these situations of moisture movement were explained with the free energy equation.

$$P = \rho RT \log (p/p_o) \qquad (2 - 1)$$

$$\text{or } \log p = \log p_o + \frac{P}{\rho RT} \qquad (2 - 2)$$

where P = hydrostatic pressure of water in soil (negative quantity with respect to flat free water surface)

ρ = density of water

R = gas constant per gram of water

T = absolute temperature

p = vapor pressure of water in soil at T

p_o = vapor pressure of free water at T

If P and ρ are considered constant, then equation (2 - 2) implies an increase in p with T when no liquid is being transferred (P = constant). Movement of water vapor in the direction of decreasing temperature would eventually result in vapor pressure equilibrium. This means p is constant and equation (2 - 1) implies a decreasing value of P (increasing negatively) with T. Therefore, liquid water would tend to flow in the direction of increasing temperature.

Dreshfield (12) has investigated the mechanism of hot-surface drying of paper sheets, a process used in the paper industry. One side of thin paper sheets was placed in contact with surface temperatures ranging between 168° to 221°F. The opposite side of the sheets was exposed to an air stream at approximately 90°F. Initial moisture contents of the sheets ranged between 115 to 235% dry basis. A water

soluble, nonsubstantive, nonvolatile dye was used to trace the liquid movement during drying. Moisture distributions during drying were determined using beta-ray transmission.

The results obtained in this work indicated that the same basic behavior prevailed throughout the range of conditions studied. Moisture distribution curves during drying are shown in Fig. 2 for a paper sheet with an initial moisture content of 200%. Typical distribution and movement patterns of water and dye are shown in Fig. 3.

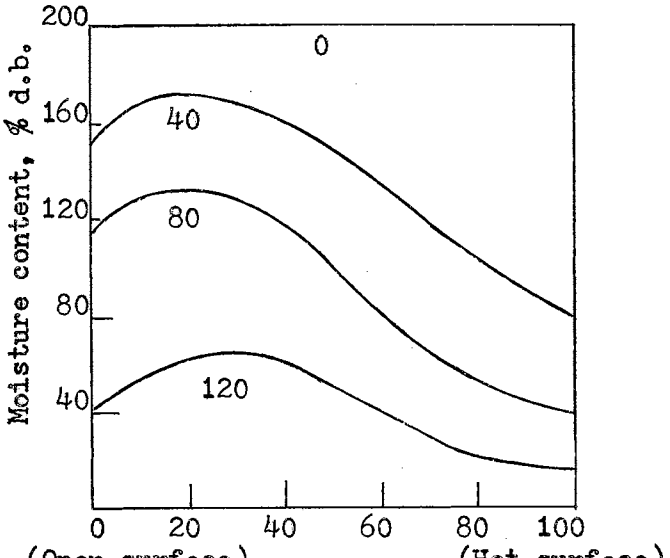

Fig. 2. Moisture Distribution in Paper Sheet During Drying with Hot Surface at 221°F.

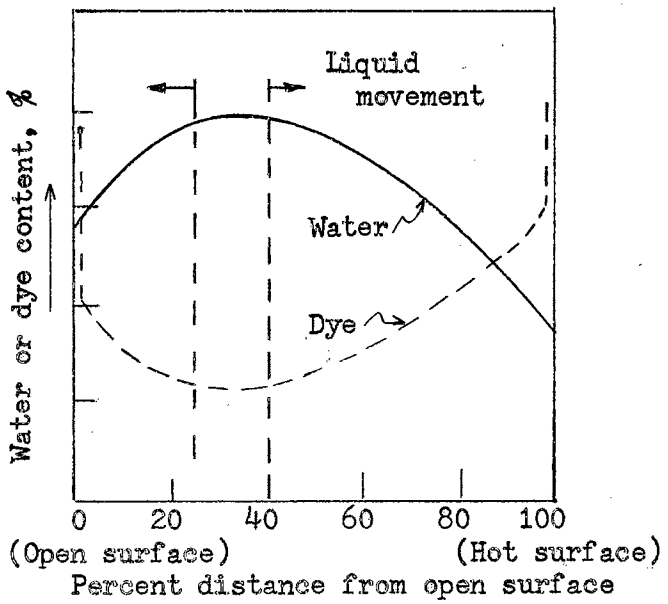

Fig. 3. Typical Distribution and Movement of Water and Dye in Paper Sheet During Drying.

During drying, the maximum moisture content was located in a zone from 20 to 30% of the distance from the open to the hot surface. In the same region, a zone of minimum dye content existed (Fig. 3). There appeared to be no movement of dye, and therefore no movement of liquid water across this zone. Liquid water which was initially between this zone and the cold surface moved toward the cold surface. The movement of liquid water was in the direction of a decreasing moisture content and was predominantly toward the hot surface of the sheet.

Dye was concentrated at both surfaces of the sheet, indicating that liquid water had moved to and evaporated at these regions. Within the sheet, the dye concentration in the liquid water decreased continuously from each surface to the region of maximum moisture content. This was also the region of minimum dye content. In this region, the dye concentration decreased relative to the initial value. Since

vaporization was occurring at the surface only, the low dye concentration indicated that the liquid water originally present in the sheet must have been diluted with water that did not contain dye. Such water could only be condensate from vapor which had been formed elsewhere. The vapor most likely came from the hot surface region since the vapor could not escape from the closed surface.

Hadley and Eisenstadt (16) conducted studies of moisture transfer due to a temperature gradient among spherical glass beads of .01 and .001 inch diameter. The sealed system was approximately 22 inches long. Temperatures at the hot end ranged between 80° and 130°F while those at the cold end ranged between 20° and 40°F. A radioactive salt was dissolved in the water to detect the presence of water in the liquid phase. The final moisture distribution was checked by the oven method.

Test results appeared independent of bead diameter. The mode of moisture movement for both hot and cold zones of the beads was apparently controlled by a critical moisture content, experimentally determined to exist between 2.5 and 4.5 percent. The physical significance of the initial moisture content appeared to be that amount of moisture causing adjacent rings of liquid to merge at the bead contacts.

Above the critical moisture content, there was no evidence of moisture movement toward the cold end when it was in an unfrozen condition (Fig. 4). It should also be noted that towards the hot end, the final radioactivity count decreases, then increases sharply while the final moisture distribution by the oven method was unchanged.

This phenomencn was explained as water evaporating at the hot surface, leaving the radioactive salt behind. After the water vapor moved toward the cold end, it apparently condensed in the region adjacent to the hot end. Liquid moving back to the hot end to compensate for the evaporation carried salt from this region to the hot end.

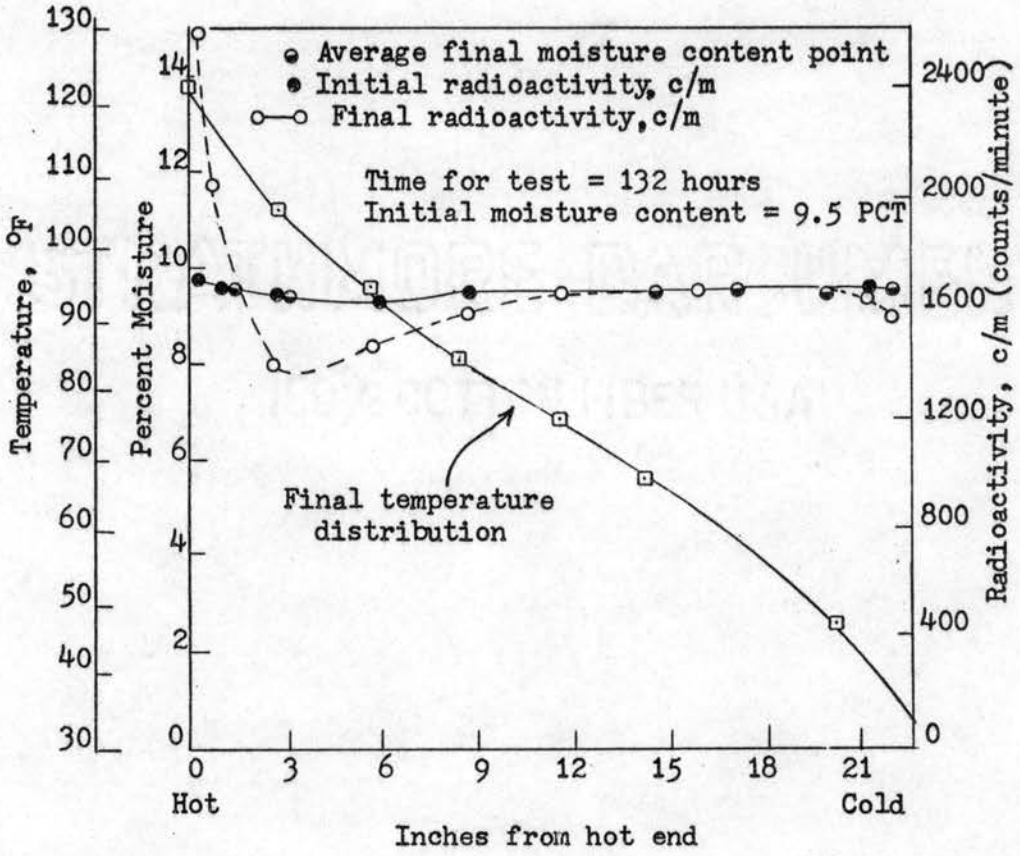

Fig. 4. Relationship of Temperature, Moisture Content, and Radioactivity to Distance in 0.01-inch Beads.

Fig. 5 shows the test results of beads above their critical moisture content with the cold end below freezing. Contrasted with the unfrozen condition, pronounced movement of water in the liquid state only towards the cold end is indicated, with moisture being supplied from the volume adjacent to the frozen zone.

Below the critical moisture content, no liquid movement was observed (Fig. 6). However a movement of moisture in the vapor state existed away from the hot end and toward the cold end. This phenomenon was independent of freezing.

Rollins and others (36) indicated that moisture movement in soils due to a temperature gradient probably occurs in the vapor phase. The principal components of the apparatus used to measure moisture movement are shown in Fig. 7. Soil was held between porous disks inside an insulated tube. The heat source and the heat sink shown produced an approximate linear temperature gradient. To form a closed system, each end of the soil tube was connected to a capillary tube filled with water. Tests were conducted with the valves in the capillary tube in the open and closed positions. The former and latter valve positions corresponded to circulating and noncirculating systems, respectively. The circulating system allowed vapor discharged from the cold end of the soil tube to return to the hot end of the soil tube. A mercury drop in the capillary permitted measurement of moisture movement when the valves were open.

The results reported were for steady state conditions. Typical

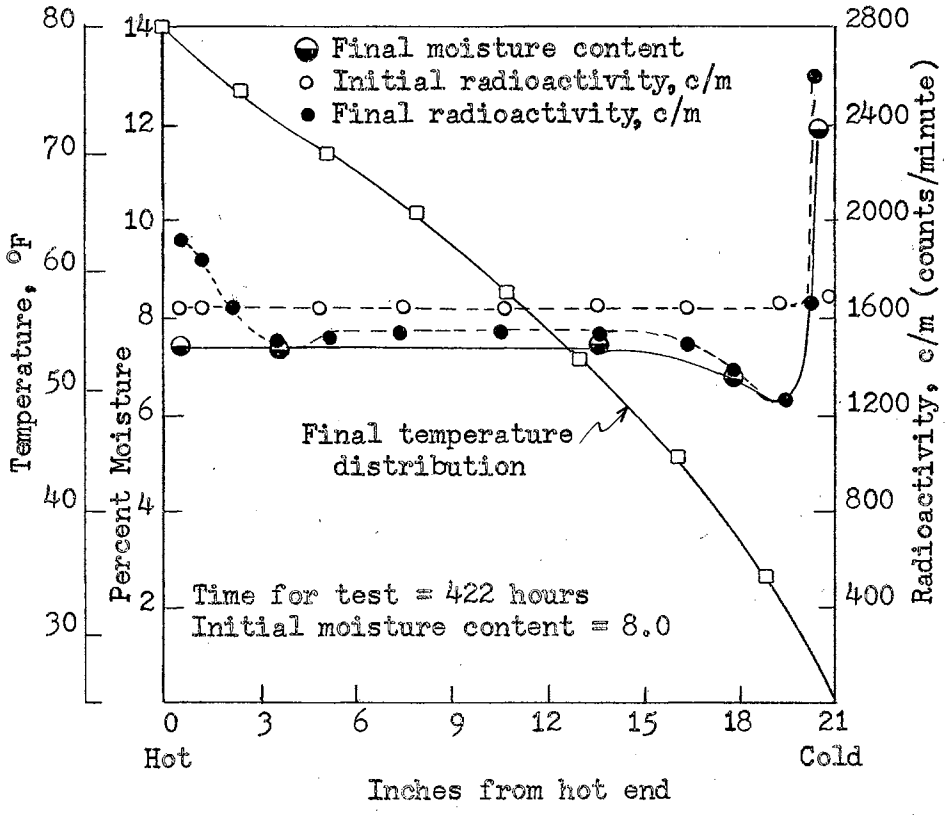

Fig. 5. Relationship of Temperature, Moisture Content, and Radioactivity to Distance in 0.01-inch Beads.

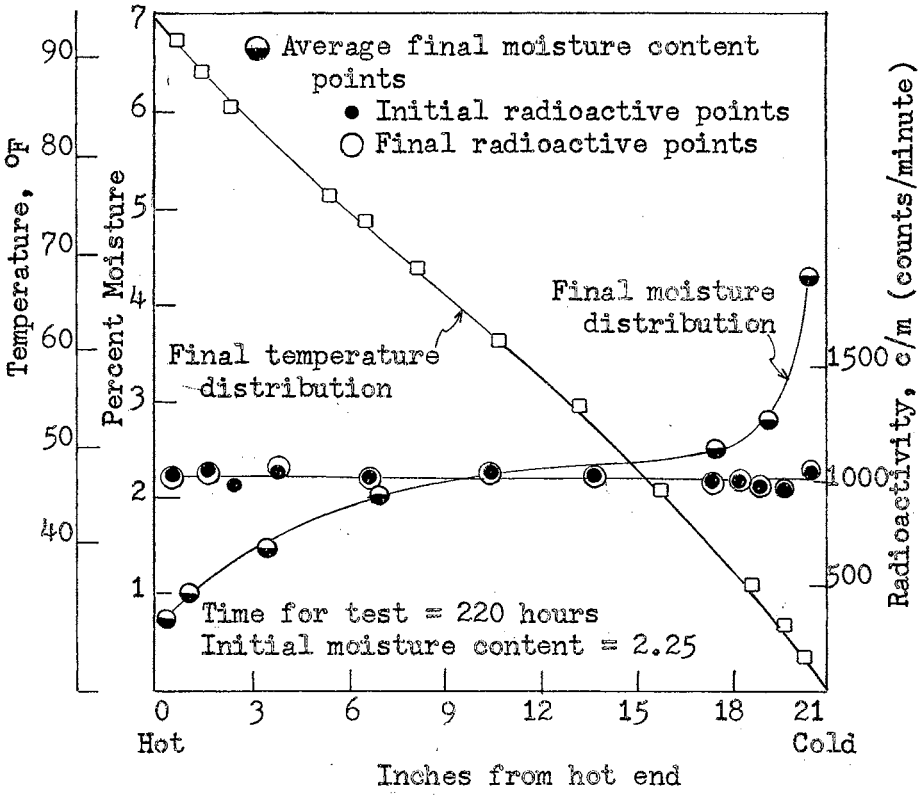

Fig. 6. Relationship of Temperature, Moisture Content, and Radioactivity to Distance in 0.001-inch Beads.

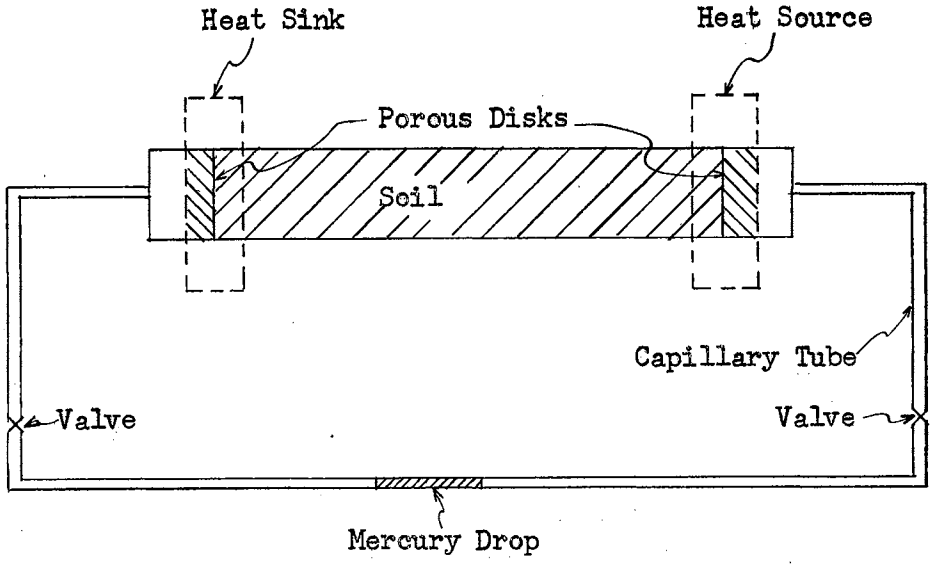

Fig. 7. Apparatus for Measuring Soil Moisture Movement.

moisture distributions determined by the oven method at the termination of the tests are shown in Figs. 8 and 9. Dry soil densities and percent air voids are indicated on each figure. Moisture accumulated in the colder portion of the tube for noncirculating systems. The moisture distribution in the circulating system was relatively uniform throughout the tube.

It was reasoned that moisture which circulates through the capillary tube during a steady state should be other than that which moves through the soil continuously in the liquid phase. Therefore, since moisture accumulated in the noncirculating system and did not appreciably accumulate in the circulating system, moisture movement in the liquid phase was not the predominant mechanism in the soils used.

For a given soil density and moisture content, the rate of moisture

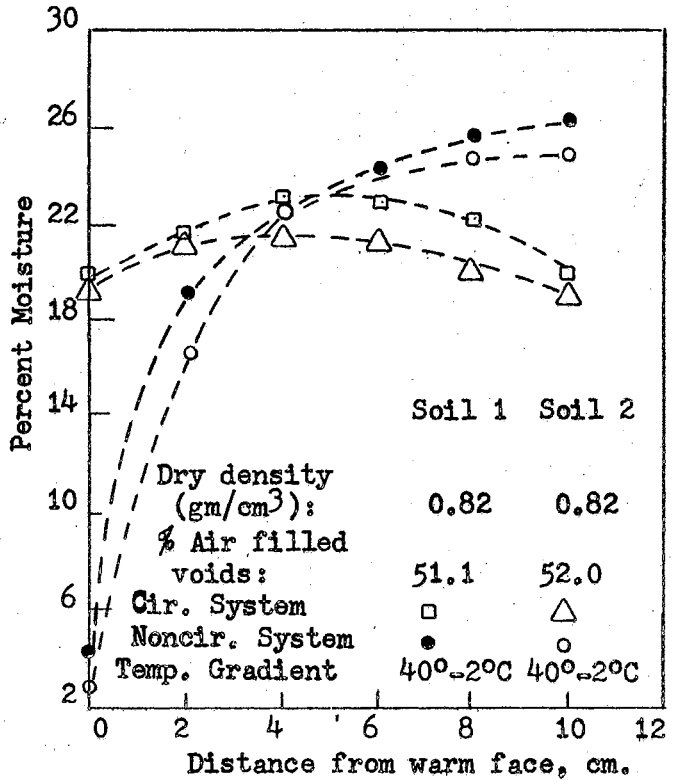

Fig. 8. Comparison of Moisture Distribution for Circulating and Noncirculating Systems.

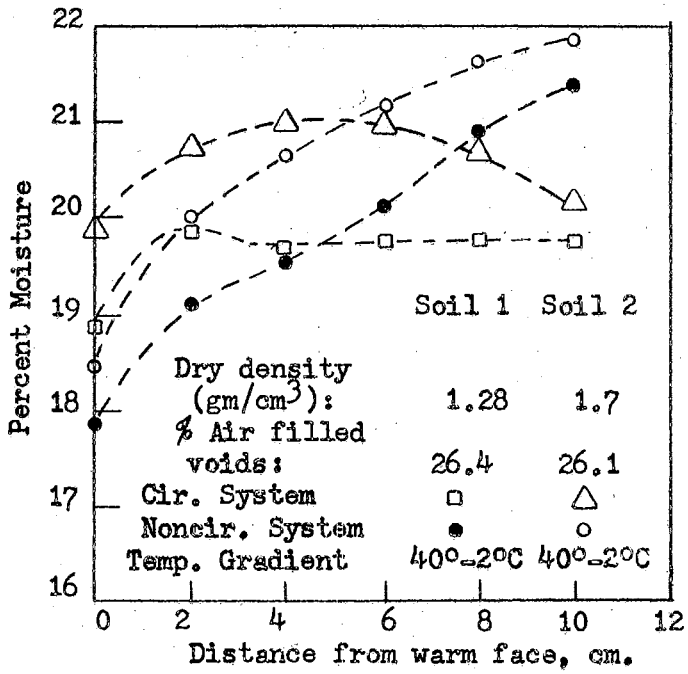

Fig. 9. Comparison of Moisture Distribution for Circulating and Noncirculating Systems.

transfer in the direction of decreasing temperature was found to be a non-linear function of the temperature gradient. Flow rates for temperature differences between the heat source and heat sink in the range of 40 to 30°C were greater than those for the 10 to 0°C range.

Water vapor movement in soils was studied by Jones and Kohnke (23). Vapor movement was effected by vapor pressure differences obtained through the application of a sharp temperature interface at the mid-point of sealed, horizontal soil columns. Movement of water vapor increased rapidly with moisture content up to a certain level, then decreased sharply. The soil moisture tension at which vapor movement was initiated and at which maximum movement occurred increased with a decrease in soil particle size. The volume of unsaturated soil pores, not their size, seemed to govern the soil moisture content at which vapor movement began. The volume of vapor movement under a given vapor pressure gradient was apparently controlled by the balance of unsaturated pore space, evaporating surfaces, and moisture reserve existing in the soil. Temperature-induced vapor pressure gradients appeared to be mainly responsible for water vapor transfer in soils. In fact, conditions in this study indicated that vapor transfer was approximately proportional to the vapor pressure gradient.

Taylor and Cavazza (43) reported results to show that moisture flow in soils due to temperature gradient was principally in the vapor phase. Sealed lucite cylinders 10 cm. long and 6.6 cm. in diameter were used to contain silt loam soil. The cylinders were insulated and were

placed between water baths at 30°C and 10°C for temperature control. The soil was placed in the cylinders either as a continuous column or as five sections separated by four air spaces perpendicular to the axis of the cylinders. The thicknesses of the air spaces were 1 to 10 mm. Typical moisture distributions in continuous and discontinuous soil columns are shown in Figs. 10 and 11, respectively. The similarity of moisture distributions in the continuous and discontinuous soil columns suggests that the moisture movement due to a temperature gradient is primarily the result of vapor flow.

The effect of temperature gradients on moisture movement in soils was studied by Matthes and Bowen (29). A sealed, one-dimensional container 10 inches long held the soil. The initial moisture content of the soil was approximately 9% dry basis. Temperatures of approximately 150° and 40°F at either end of the one-dimensional container formed the temperature gradient.

The moisture change in the soil at a point was predicted with Fick's Second Law (transient diffusion equation) and verified by weight measurements. The diffusion coefficient was considered as a variable. The water vapor concentration in the soil pore spaces was expressed as a function of temperature. The function assumed that the water vapor in the soil pores was always saturated. This allowed water vapor concentration changes to be estimated by temperature measurements.

It was observed that the moisture moved from hot to cold regions. The equation developed appeared to predict the correct trends of moisture

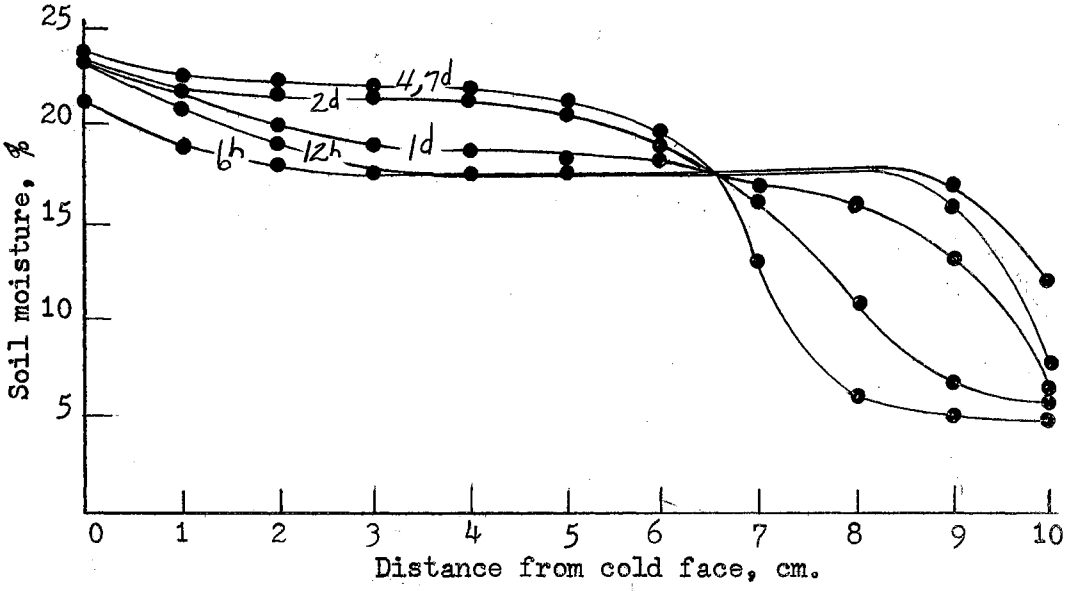

Fig. 10. Moisture Distribution in Continuous Soil Columns at 6 and 12 Hours and 1, 2, 4, and 7 Days After a Temperature Gradient Was Established.

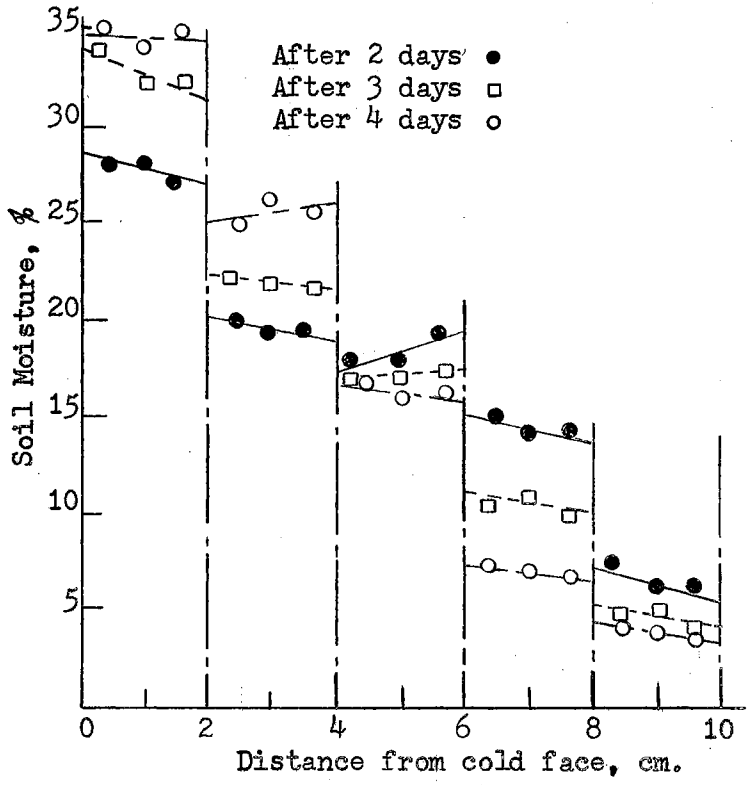

Fig. 11. Moisture Distribution as a Function of Distance From the Cold Face in Soil Column Broken Only by Air Gaps at Various Times After a Temperature Gradient Was Established.

change at different points in the soil. However, it was felt that the imprecision of the testing methods prevented verification of the equation.

Kuzmak and Sereda (26) made a study of the influence of a vapor gap on the rate of water movement through ceramic porous materials. Their setup was two flat, ceramic, porous plates with a small vapor gap between the inner faces of the two plates. The outer faces of the plates were exposed to different temperatures to develop a temperature gradient. With each of the outer faces of the plates in contact with water in the liquid phase, there was no moisture transfer as long as the gap remained saturated with liquid. Flow began when the gap began to unsaturate. Maximum flow was attained when the gap contained the least amount of liquid. They concluded that moisture movement due to a temperature gradient across a porous material takes place in the vapor phase.

In other studies with the apparatus described above, Kuzmak and Sereda (27) placed sand between the two plates. Using salt as a tracer of liquid movement, they found that the rate of salt transfer was the same with temperature gradients and isothermal conditions. The rate of salt transfer was much smaller than that anticipated had the moisture transfer occurred entirely in the liquid phase. This observation led them to check the amount of salt transferred as a result of suction gradients across the plates. Under isothermal conditions, the quantity of salt transferred indicated that the suction gradient caused moisture

transfer in the liquid phase. The results of these experiments indicated that there is no flow in the liquid phase from hot to cold regions when water moves due to a temperature gradient in a partially saturated porous material.

The independency of liquid water movement in solids and temperature gradients is further supported by other studies. Mann and others (28) dried sand by adding heat with radio-frequency fields. Comparing their results with those of other investigators who utilized different methods of heating -- that is, convection, conduction and radiation -- they found that the movement of liquid water was not influenced by the method of heating.

Philip and DeVries (33) developed two theories of moisture transfer in soils. The first theory assumed vapor diffusion as the principal contributor to moisture transfer in relatively dry soils. In the second theory, it was assumed that moisture transfer in wet soils was chiefly a result of liquid flow by Darcy's Law. The mass flux of moisture in the second theory (liquid) was separated into three components -- that due to the temperature gradient, that due to the moisture gradient, and that due to gravity. The two theories were then combined to give a general differential equation describing moisture movement in porous materials under combined temperature and moisture gradients. This theory implied that what previous investigators had supposed was vapor transfer due to temperature gradients, had actually been series-parallel flow through liquid deposits in a vapor continuum.

CHAPTER III

THEORY

Introduction

When the moisture content of a hygroscopic solid changes, water must move from all parts of the solid to or from the surface. The mode by which water is transferred to the surface is not completely known. The transfer mode assumed in the following discussion is that of water vapor diffusion through the pore spaces of the solid.

Consider a hygroscopic solid in equilibrium with its surrounding pore spaces. An increase or decrease in the water vapor concentration in the pore spaces causes the solid to absorb or evolve water, respectively. Absorption and evolution of water by the solid results in its evolution and absorption of heat, respectively. Finally, this heat will diffuse through the solid, causing changes in temperature, which affects the ability of the solid to absorb or evolve water. Thus, the transfer of moisture and the transfer of heat are the two processes involved. They are coupled together and, in general, should be considered simultaneously.

To mathematically describe the effect of simultaneous diffusion of heat and water vapor in a hygroscopic solid, the following relationship is needed.

$$M = M_1 (T, C) = M_2 (T, P)$$

where M = moisture content of solid

M_1 = function involving T and C

T = absolute temperature of solid

C = water vapor concentration adjacent to solid

M_2 = function involving T and P

P = water vapor pressure adjacent to solid

Various equations have been developed to relate these quantities. One equation used to describe agricultural products is Henderson's (19).

$$M^n = \frac{-\ln (1 - p/p_s)}{kT}$$

where M = moisture content of the solid, $\frac{\text{lbs. water}}{\text{lb. dry solid}}$

T = absolute temperature of solid, degrees Rankine

p = vapor pressure of water vapor surrounding solid, $\frac{\text{lbs.}}{\text{in.}^2}$

p_s = saturation vapor pressure of water at T, $\frac{\text{lbs.}}{\text{in.}^2}$

n = constant

k = constant, $(\text{degrees Rankine})^{-1}$

Formulation of a mathematical solution using an equation such as Henderson's would be very difficult. Therefore, a mathematical treatment similar to that first used by Henry (21) is presented.

Equilibrium Equation

Fig. 12 shows a simplified cross-section of a portion of a hygroscopic solid containing spaces filled with a mixture of water vapor and air. The solid is assumed in equilibrium with the surrounding spaces. The amount of water absorbed by the solid is assumed to have a linear dependence on the temperature of the solid and the water vapor concentration in the spaces such that

$$M = c + aC - bT \qquad (3-1)$$

where M = quantity of moisture absorbed by the solid, $\frac{\text{lbs. } H_2O}{\text{lb. dry solid}}$

C = concentration of water vapor in the spaces, $\frac{\text{lbs. } H_2O}{\text{ft.}^3}$

T = absolute temperature of the solid, $^{\circ}R$

a, b, c = constants

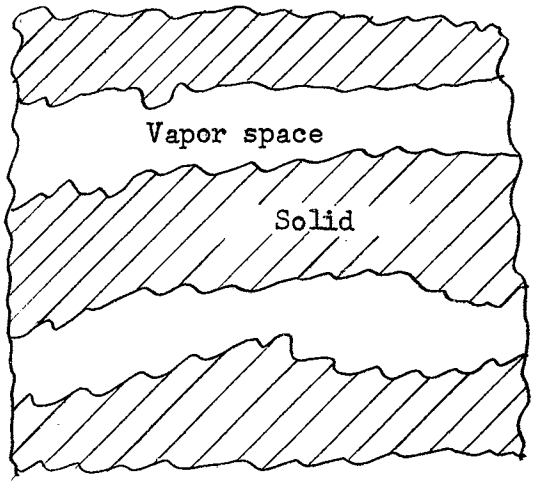

Fig. 12. Simplified Cross-Section of Hygroscopic Solid.

The above equation is approximately true for small changes of temperature and vapor concentration since the tendency for the solid to absorb water is decreased with increasing temperature and is increased with increasing vapor concentration in the spaces. Equation (3 - 1) also describes the ability of the solid to evolve water.

Vapor Diffusion Equation

The diffusion process of the water vapor in the spaces and the solid is assumed to proceed according to Fick's First Law. The amount of water absorbed by an element of volume is equivalent to the increase of vapor concentration in the space plus the increase of water in the solid. Expressed mathematically, the movement of vapor is given by

$$D_s \frac{\partial^2 C}{\partial x^2} = f \frac{\partial C}{\partial t} + (1-f)\, d_s \frac{\partial M}{\partial t} \qquad (3 - 2a)$$

where f = fraction of total volume occupied by the mixture of water vapor and air

$1-f$ = fraction of total volume occupied by the solid

d_s = density of dry solid, lbs./ft.^{3} of solid

t = time, hours

D_s = coefficient of diffusion of water vapor in the solid, ft.^{2}/hr.

x = coordinate of unidirectional vapor movement, ft.

Heat Diffusion Equation

Consider the conduction of heat within the solid which is heated such that a constant temperature is maintained at a plane surface. The rate of temperature change in a volume element is controlled by the heat conduction through the spaces and solid and the heat required to evaporate water from the solid into the spaces. The mathematical expression describing the heat conduction is

$$c_s d \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} + hd \frac{\partial M}{\partial t} \qquad (3 - 3a)$$

where c_s = specific heat of solid, $\frac{\text{Btu.}}{\text{lb. } ^\circ\text{F.}}$

K = overall thermal conductivity of the solid and spaces, $\frac{\text{Btu.}}{\text{hr. ft. } ^\circ\text{F.}}$

d = bulk density of spaces and solids in bulk, $\frac{\text{lbs. solid}}{\text{ft.}^3 \text{ of overall vol.}}$

h = heat required to evaporate water into the spaces, $\frac{\text{Btu.}}{\text{lb. } H_2O}$

Equation (3 - 3a) neglects the heat content of the vapor within the spaces.

Assumptions in Vapor and Heat Diffusion Equations

The preceding equations are based on the following assumptions:

1. The relative volume occupied by the spaces and solid remain constant.

2. The solid and adjacent spaces are in equilibrium.
3. The change in moisture content of the solid is linearly dependent on changes in temperature and vapor concentration.
4. D_s, K, c_s, and d are constants.
5. The heat associated with the loss or regain of moisture by the solid is the same.
6. Capillarity does not influence the movement of moisture within the spaces.

General Solution of Vapor and Heat Diffusion Equations

The equations involving moisture and heat movement are coupled and must be considered simultaneously. Equation (3 - 2a) can be written

$$D_s \frac{\partial^2 C}{\partial x^2} - f \frac{\partial C}{\partial t} - (1-f)\, d_s \left[\frac{\partial M}{\partial T} \frac{\partial T}{\partial t} + \frac{\partial M}{\partial C} \frac{\partial C}{\partial t} \right] = 0 \qquad (3 - 2b)$$

since $\frac{\partial M}{\partial t} = \frac{\partial M}{\partial T} \frac{\partial T}{\partial t} + \frac{\partial M}{\partial C} \frac{\partial C}{\partial t}$

Likewise, equation (3 - 3a) can be written

$$c_s d \frac{\partial T}{\partial t} - K \frac{\partial^2 T}{\partial x^2} - hd \left[\frac{\partial M}{\partial T} \frac{\partial T}{\partial t} + \frac{\partial M}{\partial C} \frac{\partial C}{\partial t} \right] = 0 \qquad (3 - 3b)$$

Equations (3 - 2b) and (3 - 3b) reduce to equations (3 - 2c) and (3 - 3c), respectively.

$$D \frac{\partial^2 C}{\partial x^2} - \frac{\partial}{\partial t} (C - GT) = 0 \qquad (3 - 2c)$$

$$H \frac{\partial^2 T}{\partial x^2} - \frac{\partial}{\partial t} (T - IC) = 0 \qquad (3 - 3c)$$

where $D = \dfrac{D_s}{d_s\, a\, (1-f) + f}$

$$G = \frac{(1-f)\, d_s\, b}{d_s\, a\, (1-f) + f}$$

$$H = \frac{K}{d\, (c_s + hb)}$$

$$I = \frac{ah}{(hb + c_s)}$$

$$\frac{\partial M}{\partial T} = -b$$

$$\frac{\partial M}{\partial C} = a$$

Multiplication of equation (3 - 2c) by $\frac{R}{D}$ and equation (3 - 3c) by $\frac{S}{H}$ yields, respectively,

$$\frac{\partial^2 (RC)}{\partial x^2} - \frac{\partial}{\partial t} \left[\frac{RC}{D} - \frac{GTR}{D} \right] = 0 \qquad (3 - 2d)$$

$$\frac{\partial^2 (ST)}{\partial x^2} - \frac{\partial}{\partial t} \left[\frac{ST}{H} - \frac{ICS}{H} \right] = 0 \qquad (3 - 3d)$$

where R and S are constants.

Addition of equations (3 - 2d) and (3 - 3d) gives

$$\frac{\partial^2}{\partial x^2}(RC + ST) - \frac{\partial}{\partial t}\left[\left(\frac{R}{D} - \frac{IS}{H}\right)C + \left(\frac{S}{H} - \frac{GR}{D}\right)T\right] = 0 \qquad (3 - 4)$$

If this equation is to be expressed as a diffusion equation, then

$$\frac{R}{D} - \frac{IS}{H} = RU^2, \quad \frac{S}{H} - \frac{GR}{D} = SU^2$$

$$\text{or} \quad \frac{\frac{R}{D} - \frac{SI}{H}}{R} = \frac{\frac{S}{H} - \frac{RG}{D}}{S} = U^2$$

$$\frac{1}{D} - \frac{IS}{RH} = \frac{1}{H} - \frac{GR}{SD} = U^2 \qquad (3 - 5)$$

This equation is a quadratic in R/S and has two roots of R/S. Elimination of R/S in equation (3 - 5) yields

$$\left[U^2 - \frac{1}{H}\right]\left[U^2 - \frac{1}{D}\right] = \frac{IG}{HD}$$

The roots are

$$U_1^2 = \frac{D + H + \left[(H-D)^2 + 4IGDH\right]^{\frac{1}{2}}}{2DH}$$

$$U_2^2 = \frac{D + H - \left[(H-D)^2 + 4IGDH\right]^{\frac{1}{2}}}{2DH}$$

Also

$$U_1^2 + U_2^2 = \frac{D + H}{DH} = \frac{1}{H} + \frac{1}{D}$$

or

$$H\,(1 - U_1^2\,D) = -D\,(1 - U_2^2\,H) \qquad (3-6)$$

From equations (3 - 4) and (3 - 5)

$$\frac{S_1}{R_1} = \left[\frac{1}{D} - U_1^2\right]\frac{H}{I} = \left[\frac{1 - D\,U_1^2}{I}\right]\frac{H}{D} = \frac{-(1 - U_2^2\,H)}{I}$$

$$\frac{R_2}{S_2} = \left[\frac{1}{H} - U_2^2\right]\frac{D}{G} = \left[\frac{1 - H\,U_2^2}{G}\right]\frac{D}{H} = \frac{-(1 - U_1^2\,D)}{G}$$

If R_1 and S_2 are equal to unity, then S_1 and R_2 are given by the two expressions above, respectively. Equation (3 - 4) can be written

$$\frac{1}{U^2}\frac{\partial^2}{\partial x^2}(RC + ST) - \frac{\partial}{\partial t}(RC + ST) = 0 \qquad (3-7)$$

The solution to (3 - 7) can be obtained by separation of variables. Assume a solution as the product of a function of x and another function of t

$$RC + ST = f(x)\,g(t)$$

where f and g are the functions. Equation (3 - 7) becomes

$$\frac{1}{U^2}\left[g\,\frac{d^2f}{dx^2}\right] = f\,\frac{dg}{dt}$$

$$\frac{1}{f}\,\frac{d^2f}{dx^2} = U^2\left[\frac{1}{g}\,\frac{dg}{dt}\right]$$

Since the left side is only a function of x and the right side is only a function of t, both sides must equal the same constant, say $-m^2$.

$$\frac{dg}{g} = \frac{-m^2}{U^2}\,dt \text{ or } g = K_1 \exp(-m^2t/U^2)$$

$$\frac{d^2f}{dx^2} + fm^2 = 0 \text{ or } f = A_1 \sin mx + B_1 \cos mx$$

Then

$$RC + ST = (A \sin mx + B \cos mx) \exp(-m^2t/U^2)$$

where $\exp(-m^2t/U^2) = e^{(-m^2t/U^2)}$

e = Naperian base of logarithms

A, B, A_1, B_1, K_1 = constants

The most general solution is the summation of the above solutions.

$$RC + ST = \sum_{n=1}^{\infty} (A_n \sin m_n x + B_n \cos m_n x) \exp(-m_n^2 t/U^2) \qquad (3-8)$$

More specifically, equation (3 - 8) represents two solutions.

$$R_1C + S_1T = \sum_{n=1}^{\infty} (A_{n1} \sin m_{n1} x + B_{n1} \cos m_{n1} x) \exp(-m_{n1}^2 t/U_1^2) \qquad (3-8a)$$

$$R_2C + S_2T = \sum_{n=1}^{\infty} (A_{n2} \sin m_{n2} x + B_{n2} \cos m_{n2} x) \exp(-m_{n2}^2 t/U_2^2) \qquad (3-8b)$$

General Solutions of Vapor and Heat Equations in Terms of Dimensionless Quantities

An equation is most useful when expressed in terms of dimensionless

quantities. Such a development for equation (3 - 8) is given in Appendix A. The general solution is equation (3 - 9).

$$R'C' + S'T' = \sum_{n=1}^{\infty} (A_n \sin m_n x' + B_n \cos m_n x') \exp(-m_n^2 t'/U'^2) \quad (3 - 9)$$

The dimensionless quantities (superscripted with prime) are defined in Appendix A. As with equation (3 - 8), equation (3 - 9) represents two solutions.

The evaluation of the constants A_n, B_n, and m_n require known boundary and initial conditions. They are illustrated in Fig. 13.

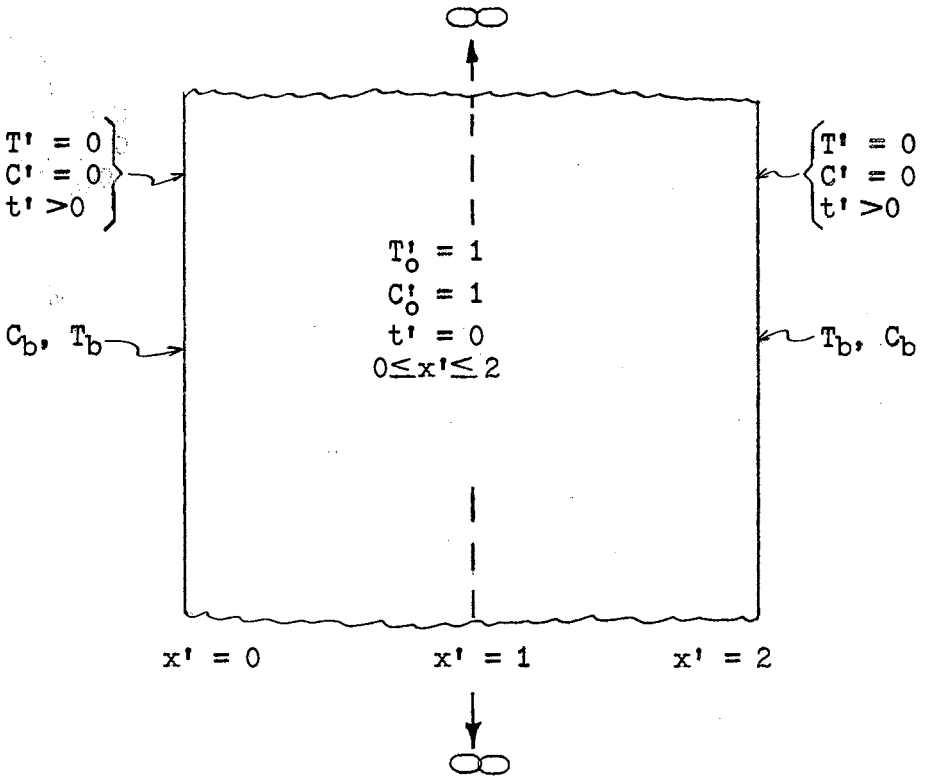

Fig. 13. Boundary and Initial Conditions on One-Dimensional Solid.

The assumed boundary conditions are

1. $T'=C'=0$, $x'=0$, $t'>0$

2. $T'=C'=0$, $x'=2$, $t'>0$

These conditions state that the boundaries of the solid ($x'=0$, 2) after time zero are held constant at T_b and C_b. The initial conditions are

$$T'=C'=1 \ , \ t'=0 \ , \ 0\leq x'\leq 2$$

These conditions state that $C = C_o$ and $T = T_o$ within the solid at time zero. Applying boundary condition (1) to equation (3 - 9) yields $B_n = 0$. Then

$$R'C' + S'T' = \sum_{n=1}^{\infty} (A_n \sin m_n x') \exp(-m_n^2 t'/U'^2) \qquad (3 - 10)$$

Application of boundary condition (2) to equation (3 - 10) gives

$$\sin (2m_n) = 0$$

For this to be an equality, the argument of the sin must be $n\pi$. Therefore, $m_n = n\pi/2$ or equation (3 - 10) becomes

$$R'C' + S'T' = \sum_{n=1}^{\infty} \left[A_n \sin \frac{(n\pi x')}{2} \right] \exp(-n^2 \pi^2 t'/4U'^2) \qquad (3 - 11)$$

Use of the initial conditions in equation (3 - 11) yields

$$R' + S' = \sum_{n=1}^{\infty} A_n \sin \frac{(n\pi x')}{2} \qquad (3 - 12)$$

Multiplying both sides of equation (3 - 12) by $\sin \frac{(m\pi x')}{2}$ and integrating from $x'=0$ to $x'=2$ yields by orthogonality

$$(R' + S') \int_0^2 \sin\left(\frac{n\pi x'}{2}\right) dx' = A_n \int_0^2 \sin\left(\frac{n\pi x'}{2}\right) dx' = A_n$$

$$A_n = \frac{4}{n\pi} (R' + S') \text{ , } n = 1, 3, 5, 7, \text{ ----}$$

The solution to equation (3 - 9) then becomes

$$R_i'C' + S_i'T' = \frac{4}{\pi} (R_i' + S_i') \sum_{n=1}^{\infty} YZ_i \qquad (3 - 13)$$

where $Y = \frac{\sin (2n-1)\pi x'/2}{2n-1}$, n = 1, 2, 3, 4, ----

$$Z_i = \exp\left[\frac{-(2n-1)^2 \pi^2 t'}{4U_i'^2}\right] \text{ , } n = 1, 2, 3, 4, \text{ ----}$$

Let $R_1' = S_2' = 1$. Then the solutions to equation (3 - 13) can be written

$$C' + S_1'T' = \frac{4}{\pi} (1 + S_1') \sum_{n=1}^{\infty} YZ_1 = V_1 \qquad (3 - 14)$$

$$R_2'C' + T' = \frac{4}{\pi} (R_2' + 1) \sum_{n=1}^{\infty} YZ_2 = V_2 \qquad (3 - 15)$$

Solving equations (3 - 14) and (3 - 15) for T' and C' gives

$$T' = \frac{V_2 - R_2'V_1}{1 - R_2'S_1'} \qquad (3 - 16)$$

$$C' = \frac{V_1 - S_1'V_2}{1 - R_2'S_1'} \qquad (3 - 17)$$

If the boundary conditions and initial conditions of C' or T' are identical, the solutions above are indeterminate. Therefore, let

$$C'_3 = \frac{C - C_b}{C_b} \quad , \quad T'_3 = \frac{T - T_b}{T_b}$$

The solutions for C'_3 and T'_3 are of the same form as those for C' and T'. However, the following constants are redefined:

$$I'_3 = I\,(C_b)/T_b \qquad G'_3 = G\,(T_b)/C_b \qquad R'_3 = S'_4 = 1$$

$$U'^2_3 = \frac{D' + 1 + \left[(D' - 1)^2 + 4I'_3 D' G'_3\right]^{\frac{1}{2}}}{2D'} \qquad S'_3 = \left[\frac{1}{D'} - U'^2_3\right] \frac{1}{I'_3}$$

$$U'^2_4 = \frac{D' + 1 - \left[(D' - 1)^2 + 4I'_3 D' G'_3\right]^{\frac{1}{2}}}{2D'} \qquad R'_4 = \left[1 - U'^2_4\right] \frac{D'}{G'_3}$$

Application of the boundary conditions

1. $T'_3 = C'_3 = 0 \quad , x' = 0 \quad , t' > 0$

2. $T'_3 = C'_3 = 0 \quad , x' = 0 \quad , t' > 0$

and the initial conditions

$$T'_3 = T'_{3i}, \; C'_3 = C'_{3i}, \; t' = 0, \; 0 \leq x' \leq 2$$

give the following solutions.

$$C'_3 = S'_3 T'_3 = \frac{4}{\pi}\,(C'_{3i} + S'_3 T'_{3i}) \sum_{n=1}^{\infty} YZ_3 = V_3 \qquad (3 - 18)$$

$$R'_4C'_3 + T'_3 = \frac{4}{\pi}\left(R'_4C'_{3i} + T'_{3i}\right)\sum_{n=1}^{\infty} YZ_4 = V_4 \qquad (3-19)$$

where $Y = \frac{\sin (2n-1)\pi x'/2}{2n-1}$, n = 1, 2, 3, 4, ----

$$Z_i = \exp\left[\frac{-(2n-1)^2 \pi^2 t'}{4U'^2_i}\right], \quad n = 1, 2, 3, 4, \text{----}$$

Equations (3 - 18) and (3 - 19) can be solved for T'_3 and C'_3 to give

$$T'_3 = \frac{V_4 - R'_4V}{1 - R'_4S'_3} \qquad (3-20)$$

$$C'_3 = \frac{V_3 - S'_3V_4}{1 - R'_4S'_3} \qquad (3-21)$$

General Solutions of Vapor and Heat Diffusion Equations in Terms of Dimensionless Quantities with Uniform Heat Generation

The case is now considered for internal heat generation. It is assumed that the heat generation, q, is uniform and constant throughout the solid. A heat balance on a differential element of the solid yields

$$c_s d \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} + hd \frac{\partial M}{\partial t} + q \qquad (3-22)$$

where $q = \frac{BtU}{hr.\ ft.^3}$

Equation (3 - 22) is simply q added to the right-hand side of equation (3 - 3a). The simultaneous solution of equation (3 - 22) and equation (3 - 2a) is derived in Appendix B in dimensionless form. Equations (3 - 16') and (3 - 17') give the solutions for C' and T', respectively.

$$C' = \frac{V_5 - S'_1 V_6}{1 - S'_1 R'_2} \qquad (3 - 23)$$

$$T' = \frac{V_6 - R'_2 V_5}{1 - S'_1 R'_2} \qquad (3 - 24)$$

V_5 and V_6 are defined in Appendix B. As with the case of no heat generation, the solutions are valid only when the initial and boundary conditions are not equal. If the boundary conditions and initial conditions of C' or T' are equal, then the solutions for uniform heat generation are

$$C'_3 = \frac{V_7 - S'_3 V_8}{1 - R'_4 S'_3} \qquad (3 - 25)$$

$$T'_3 = \frac{V_8 - R'_4 V_7}{1 - R'_4 S'_3} \qquad (3 - 26)$$

where $V_7 = N_3 + \frac{4}{\pi} \sum_{n=1}^{\infty} W_3 \, YZ_3$ $\qquad$ $V_8 = N_4 + \frac{4}{\pi} \sum_{n=1}^{\infty} W_4 \, YZ_4$

$$N_3 = \frac{J'_3}{2}\left[2x' - (x')^2\right]$$

$$N_4 = \frac{J'_4}{2}\left[2x' - (x')^2\right]$$

$$J'_3 = \frac{S'_3 Q' D' I'_3}{F'_3}$$

$$J'_4 = \frac{Q' D' I'_3}{F'_3}$$

$$F'_3 = aC_b$$

$$W_3 = C'_{3i} + S'_3 T'_{3i} - \frac{4J'_3}{(2n-1)^2\pi^2}$$

$$W_4 = R'_4 C'_{3i} + T'_{3i} - \frac{4J'_4}{(2n-1)^2\pi^2}$$

Water Lost by the Solid

In the following discussion, the amount of water lost from one surface of a one-dimensional solid is derived. The case in which boundary and initial conditions of either C' or T' are identical is considered.

The water vapor flux rate, B, from the solid surface ($x' = 2$) is given by Fick's First Law as

$$B = -D_s \frac{\partial C}{\partial x} = -D_s \frac{\partial C}{\partial x'} \frac{\partial x'}{\partial x} = \frac{-D_s}{L} \frac{\partial C}{\partial x'} \qquad (3 - 27)$$

where $B = \frac{\text{lbs. water}}{\text{hr. ft.}^2}$

and equation (3 - 27) is evaluated at $x' = 2$.

The amount of water, A, lost at the solid surface ($x' = 2$) after time t has elapsed is

$$A \int_0^t B \, dt = \frac{-D_s}{L} \int_0^t \frac{\partial C}{\partial x'} \, dt \qquad (3 - 28)$$

where $A = \frac{\text{lbs. water}}{\text{ft.}^2}$

Consider the case of uniform heat generation. Equation (3 - 25) can be solved for C to yield

$$C = C_b + C_b \left[\frac{V_7 - S_3' V_8}{1 - R_4' S_3'} \right] \qquad (3 - 29)$$

Substituting equation (3 - 29) into equation (3 - 28) and integrating gives

$$A_g = \frac{2 D_s C_b}{L (1 - R_4' S_3')} \left[\sum_{n=1}^{\infty} W_3 E_1 (1 - Z_1) - S_3' (W_4)(E_2)(1 - Z_2) \right] \qquad (3 - 30)$$

where $E_1 = \frac{4 U_1'^2 L^2}{(2n-1)^2 \pi^2 H}$

$$E_2 = \frac{4 U_2'^2 L^2}{(2n-1)^2 \pi^2 H}$$

and the g subscript indicates uniform heat generation.

Similarly, the case without uniform heat generation yields

$$A_o = \frac{2D_s C_b}{L\,(1-R_4' S_3')}\left[\sum_{n=1}^{\infty} W_1 E_1 (1-Z_1) - S_3'(W_2)(E_2)(1-Z_2)\right] \qquad (3-31)$$

where $W_1 = C'_{3i} + S'T'_{3i}$

$$W_2 = R_4' C'_{3i} + T'_{3i}$$

and the o subscript indicates no heat generation.

Equations (3 - 30) and (3 - 31) can be made dimensionless by multiplying each by $L/D_s C_b$. Then the following dimensionless term is defined.

$$A_i' = \frac{A_i L}{D_s C_b} \qquad (3-32)$$

Theoretical Predictions for One-Dimensional Peanut Kernel

One of the objectives in this study was to determine the significance of a temperature gradient in controlling the moisture gradient during the curing process in a model representing the peanut kernel. The purpose of this section is to present theoretical predictions concerning the above objective using the theory developed in this Chapter.

The peanut kernel was assumed to have a geometrical configuration of an infinite plate with a thickness 2L. The finite dimension of the

kernel corresponded to the x coordinate. Since the conditions in the kernel would be symmetrical about its center, x = L, only one-half the kernel ($0 \leq x \leq L$) was considered.

Values assumed for the constants introduced in equations (3 - 2a) and (3 - 3a) were:

$f = 0.01$

$d_s = 71.0$

$D_s = 0.01$

$c_s = 0.5$

$d = 70.0$

$h = 1000$

$K = 0.08$

The initial conditions of C and T were:

$C = 0.001105$

$T = 540$

The boundary conditions of C and T were:

$C = 0.000720$

$T = 540$

The heat generation rate, q, was 8800. L was .35 cm. or 0.0115 ft. Constants a, b, and c in equation (3 - 1) were calculated with moisture equilibrium data of peanut kernels (17) (24). These values were:

$a = 153$

$b = 0.0019$

$c = 0.9959$

For the case of no heat generation, equations (3 - 20) and (3 - 21) were solved for T and C. On the other hand, equations (3 - 25) and (3 - 26) were solved for C and T for the case of uniform heat generation. M, C, T, and A_1' were then evaluated using the assumed values stated.

Fig. 14 shows the temperature distributions in the kernel after one hour of elapsed drying time. The respective distributions remained essentially unchanged up to 73 hours of elapsed drying time. With heat generation, the temperature difference between the surface and center of the kernel was approximately 7 ^{o}R. Without heat generation, the temperature distribution was almost uniform.

Fig. 15 shows the amount of water lost per unit surface area as a function of drying time. Note that the distance between the curves increased with time. This indicated that the water vapor flux at the kernel surface was always greater with heat generation. The greater vapor flux with heat generation was the result of a greater concentration gradient at a given elapsed drying time. Fig. 16 shows the concentration distribution in the kernel at 25 and 61 hours of elapsed drying time.

In Fig. 17, the moisture distributions in the kernel are shown after 25 and 61 hours of elapsed drying time. The parameter at the right end of the curves is A'. With and without heat generation, the shape of the curves appeared to be the same. However, for given elapsed drying times, the steeper moisture gradient corresponded to the case with no heat generation. These curves indicated two effects of heat

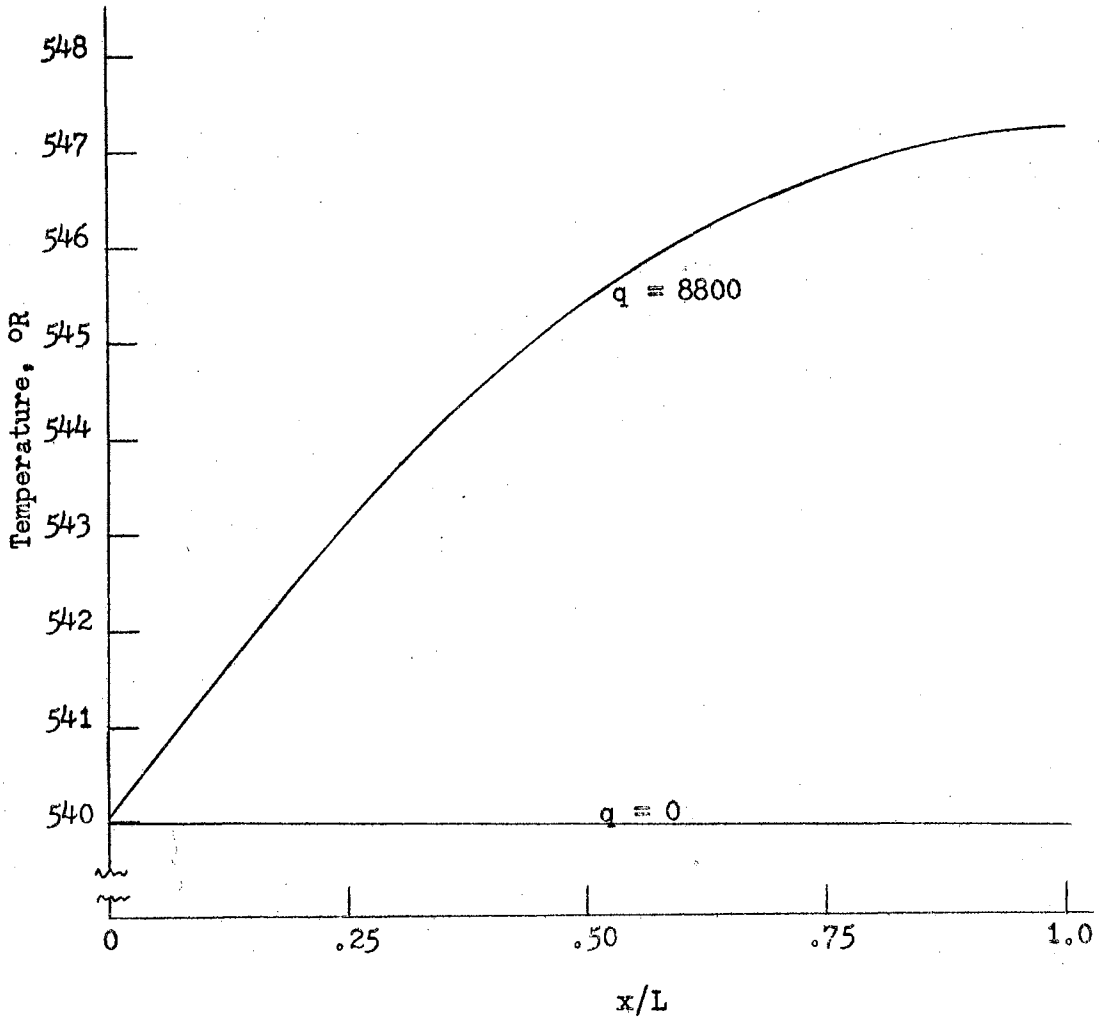

Fig. 14. Temperature Distributions in One-Dimensional Peanut Kernel.

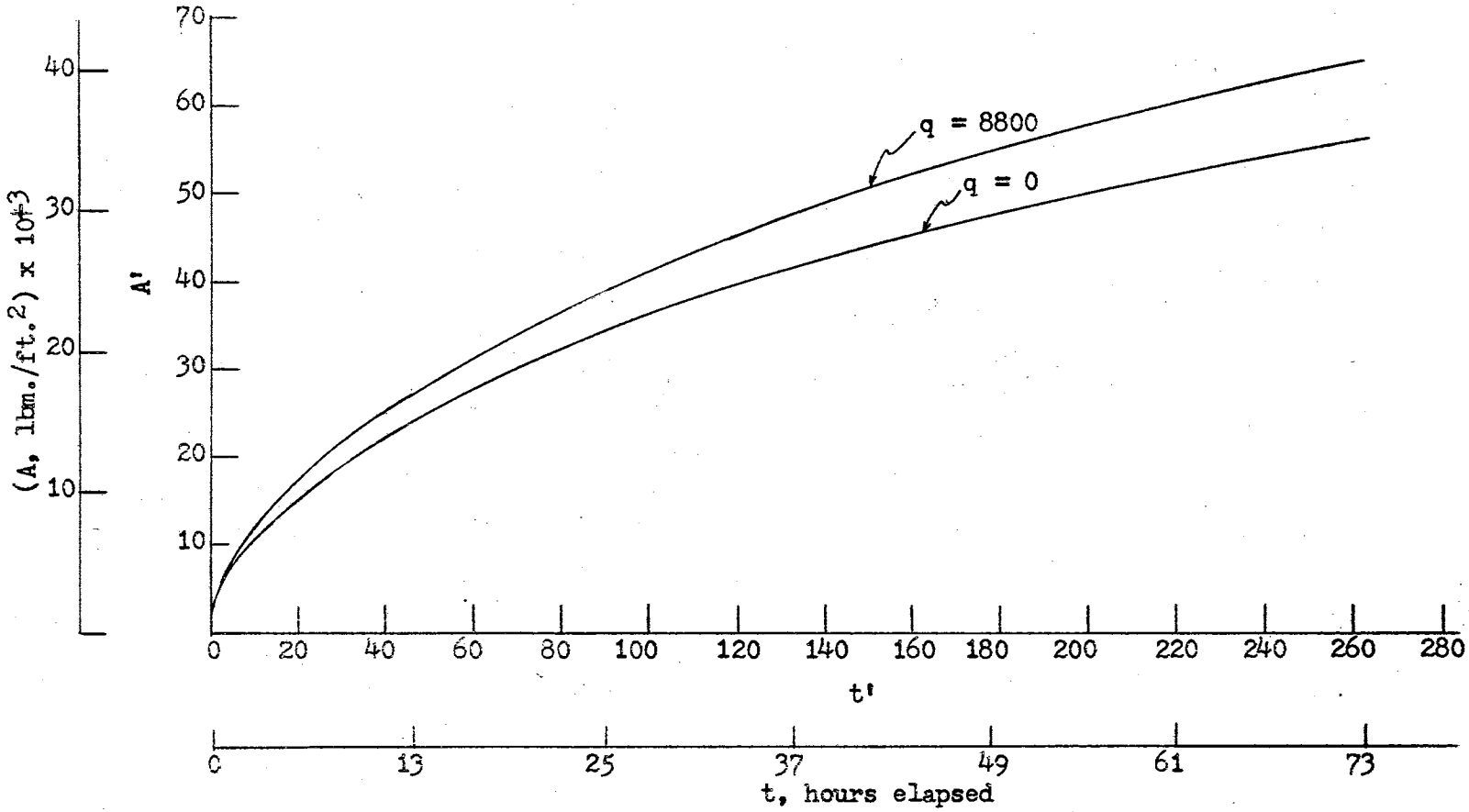

Fig. 15. Water Lost from One Surface of One-Dimensional Peanut Kernel as a Function of Time.

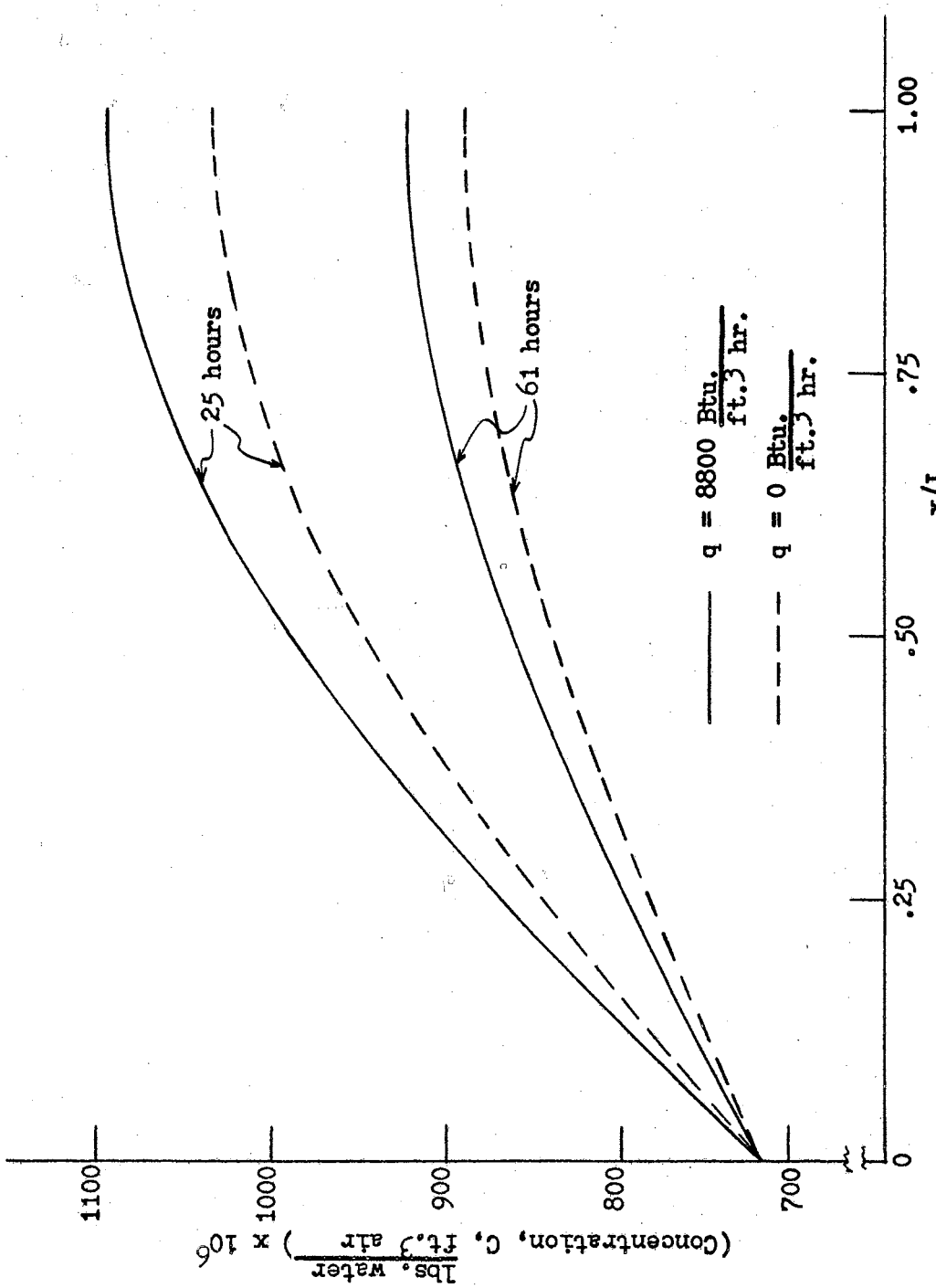

Fig. 16. Water Vapor Concentration Distributions in One-Dimensional Peanut Kernel.

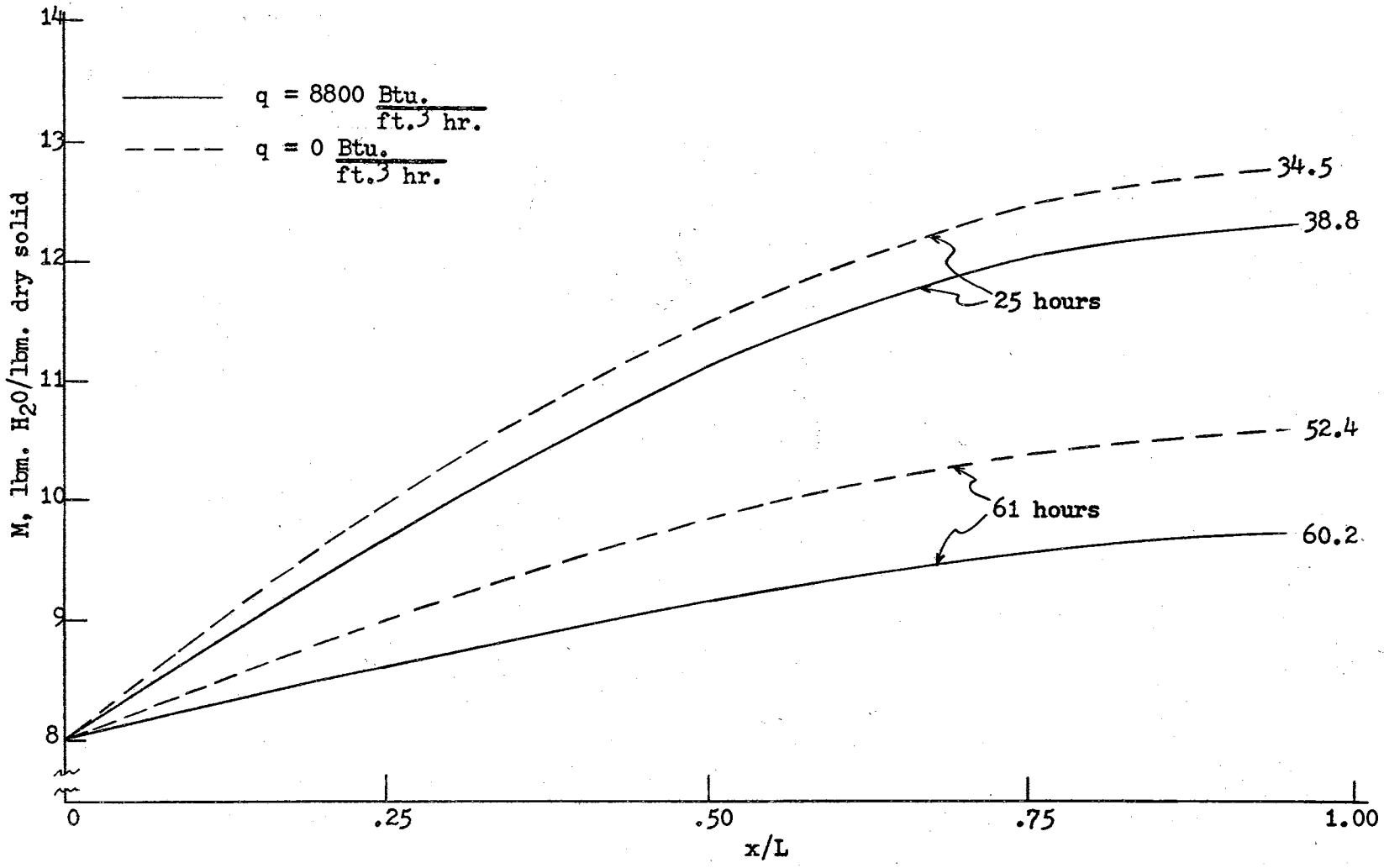

Fig. 17. Moisture Distributions in One-Dimensional Peanut Kernel.

generation for given initial and boundary conditions of the kernel. First, the amount of heat generation had negligible effect on the moisture distribution for a given quantity of water lost from the kernel surface. Second, heat generation decreased the time required to obtain a given kernel moisture distribution and to remove a given quantity of water through the kernel surface.

Dimensional Analysis

The time and labor involved in evaluating parameters of the drying experiment in preliminary tests indicated that dimensional analysis would be advantageous. With dimensional analysis, a number of measurable test parameters are used to form a smaller number of dimensionless ratios or Pi terms. The Buckingham Pi Theorem states that the number of dimensionless and independent ratios is equal to the number of parameters involved minus the number of dimensions in which those parameters are measured. Pi terms can be treated as variables. Dimensional analysis also offers the possibility of formulating a general prediction equation relating the dependent parameter to all other parameters appearing in variable Pi terms.

Laboratory observations are necessary to formulate the prediction equation. According to Murphy (31), the most advantageous procedure for evaluating the function is to arrange the observations so that only one of the Pi terms involved in the function is varied, while the other Pi terms in the function remain constant. The relationship resulting

between the dependent and independent or varied Pi term is known as a component equation. This procedure is repeated with each Pi term in the function. The function relating the dependent Pi term and the remaining Pi terms requires that the component equations be combined in some manner. If the component equations are of the form $\Pi_1 = C_i \Pi_i^x$, the Pi terms will combine by multiplication and the general prediction equation will have the form of equation (3 - 50).

$$\Pi_1 = C \Pi_2^{x2} \Pi_3^{x3} \Pi_4^{x4} \text{ ---- } \Pi_i^{xi} \qquad (3 - 50)$$

If the component equations are of the form $\Pi_1 = K_i + C_i \Pi_i$, the Pi terms will combine by summation and the general prediction equation will take the form of equation (3 - 51).

$$\Pi_1 = K_1 + K_2 \Pi_2 + K_3 \Pi_3 + \text{----} + K_i \Pi_i \qquad (3 - 51)$$

Pertinent Variables in the Drying Investigation

A schematic of the system chosen for the drying investigation is shown in Fig. 18. Corn meal used as the test material was placed inside a glass tube which was surrounded by insulation and sealed at one end. The sealed end of the tube was held at temperature, T_L. Corn meal at the open end of the tube was subjected to a temperature, T_o, and a water vapor pressure, P_o.

The dimension of each parameter believed to be important in the drying system is shown in TABLE I.

TABLE I

BASIC PARAMETERS IN THE DRYING SYSTEM

No.	Symbol	Parameter	Dimension
1	L	Length of one-dimensional system, ft.	L
2	T_o	Temperature at open end of system, ^oR.	θ
3	T_L	Temperature at closed end of system, ^oR.	θ
4	D	Diffusion coefficient for water vapor through the void spaces in the corn meal at 81^oF, $ft.^2/hr.$	L^2T^{-1}
5	P_o	Vapor pressure of water vapor at open end of system, $lbf./ft.^2$	FL^{-2}
6	M_i	Initial moisture content (dry basis) of the corn meal, (lbm./lbm.) 100.	0
7	x	Reference distance from open end of system, ft.	L
8	M_x	Moisture content (dry basis) at x, (lbm./lbm.) 100.	0
9	t	Time elapsed, hrs.	T
10	k	First constant describing hygroscopic characteristics of kernel corn, $1/^oR$.	θ^{-1}
11	n	Second constant describing hygroscopic characteristics of kernel corn.	0
12	P_s	Saturation vapor pressure at temperature at open end of system, $lbf./ft.^2$	FL^{-2}
13	W	Molecular weight of water, lbs./lb. mole	0
14	R	Mass of water lost by system per dry unit mass of corn meal at time t, lbm./lbm.	0

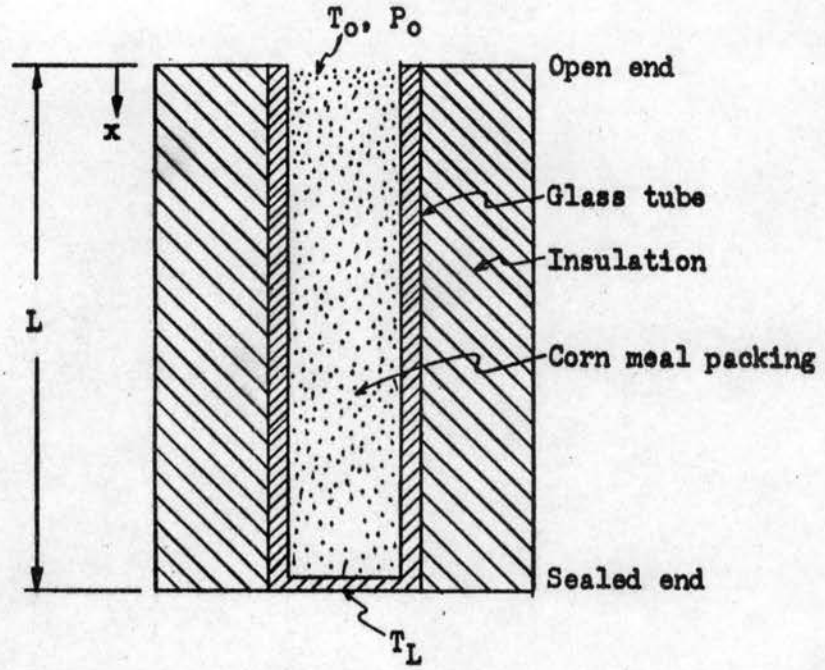

Fig. 18. Schematic of Cross-Section of System Used in Drying Investigation.

The dimensions used in TABLE I were:

F = Force T = Time

θ = Temperature L = Length

The number of Pi terms = 14 - 4 = 10. The set of Pi terms used was:

$\Pi_1 = M_x$

$\Pi_2 = R$

$\Pi_3 = n$

$\Pi_4 = W$

$\Pi_5 = T_o/T_L$

$\Pi_6 = T_o k$

$\Pi_7 = x/L$

$\Pi_8 = M_i$

$\Pi_9 = Dt/L^2$

$\Pi_{10} = P_o/P_s$

The thermal properties of the corn meal were not included since unsteady state conditions of temperature in the drying tests were almost non-existent. Parameters 10, 11, and 12 are those in Henderson's equation (19) describing hygroscopic characteristics of kernel corn. It is assumed that the corn meal and kernel corn exhibit similar hygroscopic characteristics.

Discussion of Pi Terms

Π_1 and Π_2 were observed simultaneously as the dependent quantities in the drying tests. Π_3, Π_4, and Π_6 were not varied during the tests. Variation of Π_3 and Π_4 involved changing the test material and diffusing vapor, respectively. Π_6 was not varied because of spoilage problems with the corn meal at high temperatures.

It was the object of the test to establish relationships between each of the dependent Pi terms and the independent Pi terms Π_5, Π_7, Π_8, Π_9, and Π_{10}. Once these relationships were established, moisture distributions could be compared for given amounts of water lost for different drying conditions.

T_o/T_L was the ratio of the temperatures at the open and sealed ends of the samples. Knowing these two temperatures and L defined the temperature conditions of any test. The temperature of the corn meal affected its equilibrium vapor pressure, which in turn affected its vapor transfer characteristics.

x/L was the ratio of the reference distance at which M_x was observed to the total length of the system.

M_i was the initial moisture content of corn meal. It described the ability of corn meal to release water at the initial stages of drying.

Dt/L^2 related the diffusion rate of the water vapor to a time and length factor. This ratio was necessary since R and M_x were time dependent and also depended on the length of the system.

P_o/P_s was the relative humidity of the air at the open end of the system. It affected R by changing the vapor pressure driving potential across the length of the system. An increase in P_o/P_s decreased R resulting in smaller changes of M_x for given elapsed drying times.

CHAPTER IV

METHODS, MATERIALS, AND APPARATUS

Method for Moisture Distribution Determination

An indirect method for measuring the moisture distribution in the drying samples was initially proposed for the following reasons:

1. The moisture distribution measurements could be made without disturbing the drying samples.
2. The moisture distribution of the drying samples could be continuously measured during a test as a function of position and time.

Preliminary investigations were conducted in an attempt to correlate moisture content and capacitance-resistance measurements on various solids. This approach seemed promising since electrical properties of hygroscopic solids change markedly with moisture content. It was found that the correlations of moisture content and capacitance-resistance measurements were satisfactory only at very low moisture contents. The distribution of water in the solids at high moisture contents apparently affected the electrical measurements.

Unsatisfactory results with the indirect method led to the use of a direct weighing method. The samples were divided into finite lengths

and weighed on an analytical balance with a sensitivity of 0.0001 gram.

Selection of the Test Material for Drying Tests

A test material with properties similar to the peanut kernel was desired. Some form of the peanut kernel was first considered. However, this material was rejected when the ease of handling was found to be important in obtaining a uniform packing density in the drying sample.

Gypsum was investigated as a test material. It was easy to handle and resulted in drying samples of uniform density. However, a uniform initial moisture distribution in the drying samples was very difficult to obtain.

Corn meal was selected as the test material. As with the peanut kernel, corn meal is hygroscopic in nature. Relatively wet corn meal was easy to handle. Uniformity of density and of initial moisture distribution in the drying samples was obtained with little difficulty. In addition, the drying rate of the corn meal was high enough to develop measurable moisture gradients in two days or less. A minimum test time was important because spoilage in the moist corn meal was usually observed after 2 days at temperatures of 80°F and greater.

Selection of a Holding Unit for the Corn Meal

A holding unit for the corn meal was necessary for two reasons. First, a container was needed to support the corn meal due to its

granular nature. Second, since one-dimensional samples were used in this study, barriers parallel to the length dimension of the samples were required. This was essential if the transfer of heat and vapor was to be significant only along one dimension.

Plastic tubing was first tested as a container to insure one-dimensional water vapor transfer. The ease of cutting the plastic tubing was convenient for moisture distribution determinations on the sample. However, water vapor transfer through the walls of the plastic tubing was appreciable. In addition, sealing the plastic tubing at one end was difficult.

Fig. 19 is a schematic of the holding unit used in the drying study.

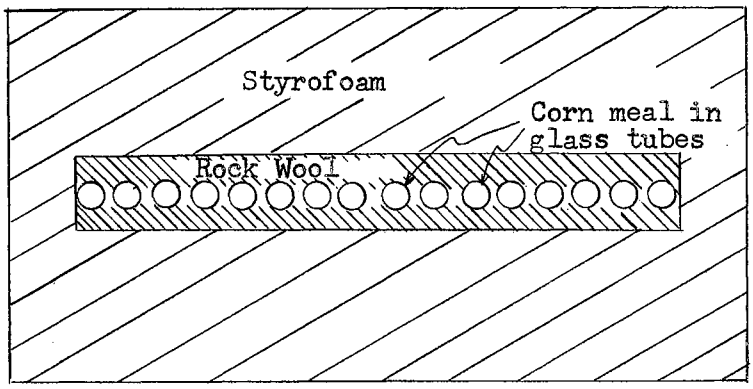

Fig. 19. Schematic of Top View of Holding Unit for Corn Meal.

The corn meal was contained in 11 mm. ID Pyrex glass tubing 8 inches in length. One end of the tubing was sealed by melting the glass. One glass tube in each test was designated as the check sample to make temperature distribution measurements. Along the length of this tube, eight-1/16 in. diameter holes were spaced one inch on centers for insertion of thermocouples. The set of holes was centered on the length of the tube.

The 11 mm. ID tubing was small enough to allow breaking of the tube into short sections. This was necessary to determine moisture distributions. On the other hand, the tubing was large enough to obtain the desired precision in weight measurements for moisture distribution determinations.

Insulation was added along the length of the tube to maximize one-dimensional heat flow. A blanket of rock wool was placed against either side of the row of glass tubes. The rock wool was held in place by styrofoam two inches thick on the sides and one inch thick on the ends. Fig. 20 shows the holding unit with one side of the rock wool and styrofoam insulation removed.

Temperature and Humidity Control Apparatus

During the drying tests, the temperature was held constant at each end of the drying sample. Also, the relative humidity at the open end of the drying samples was held constant.

Air was circulated in two closed, insulated ducts to control the conditions at each end of the drying samples. The apparatus without

its insulation cover is shown in Fig. 21. It was suspended from the ceiling of a room in which the temperature was controlled within $\pm 2^{\circ}F$.

Figs. 22 and 23 schematically show the components of the top and bottom ducts, respectively. The ducts were constructed of sheet metal tubing with a six-inch ID. Rock wool insulation one inch thick covered the two ducts. A damper in each duct regulated the amount of air circulation.

Air was circulated in the top duct with a small centrifugal fan. The open ends of the drying samples were exposed to conditions in the duct. Holes in a foam rubber piece cemented to the bottom of the duct held the top of each drying sample. The relative humidity of the air stream was controlled with salt solutions. The solutions were held in plastic pans 3/4 in. x 6 in. x 12 in. fitted to the bottom of the duct.

A small fan was mounted inside the bottom duct to circulate air. Four straight, aluminum fins of rectangular profile were placed in the air stream of the duct. The air moved parallel to the flat surface of the fins. A rectangular trough partially filled with oil was secured to the top of the fins with an aluminum metallic paste. The sealed ends of the drying samples were submerged in the oil in the trough. The fins and the oil bath transferred heat between the air stream and the sealed end of the drying samples.

The air was heated and cooled in both duct systems in the same way. A 400-watt heater was the heat source. Adjustment of the voltage to the heater with a variable transformer controlled its

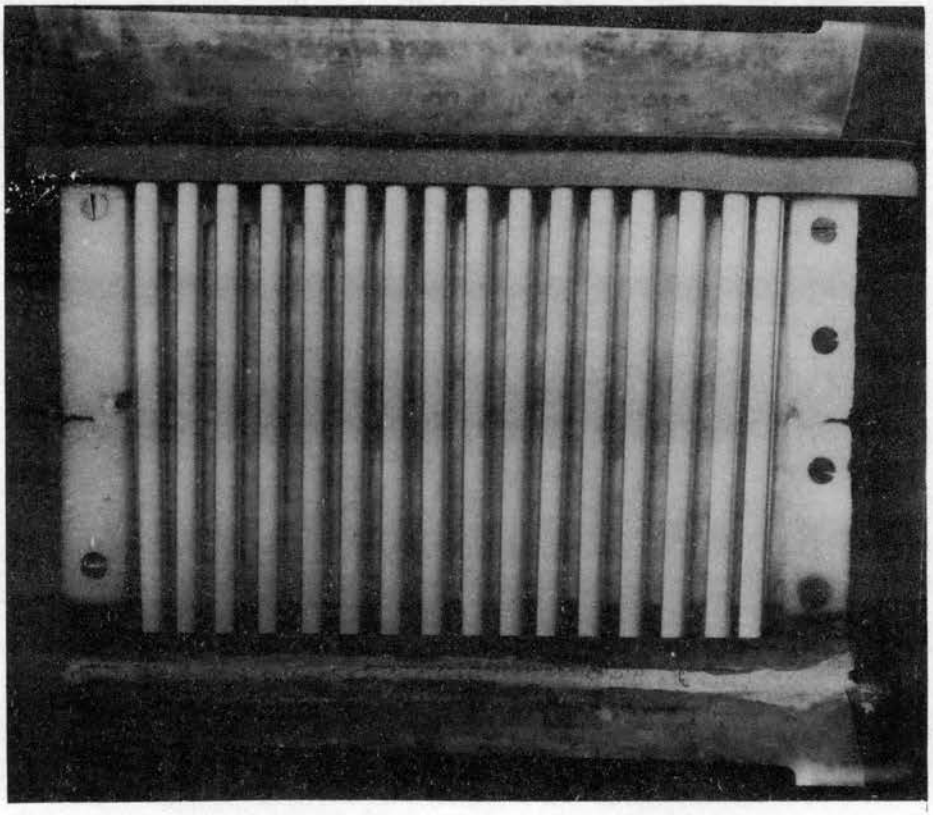

Fig. 20. Placement of Samples in Holding Unit.

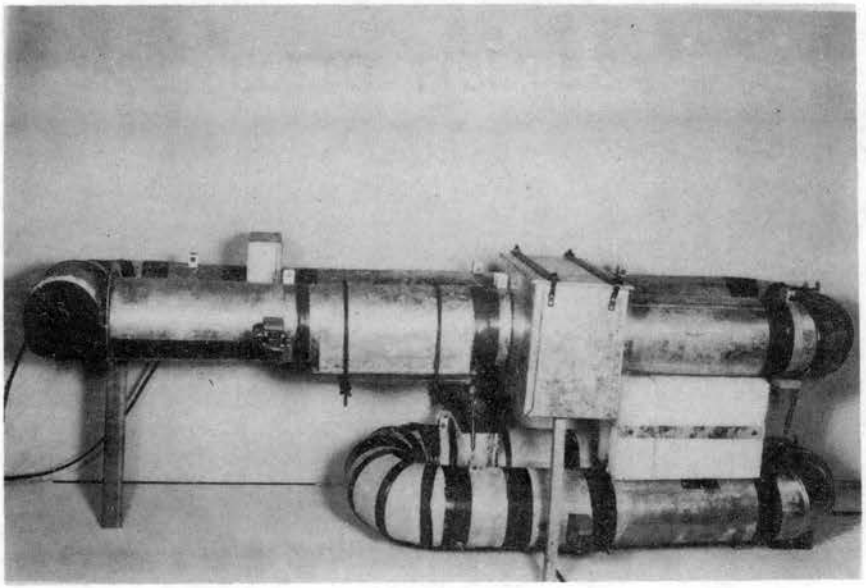

Fig. 21. Drying Apparatus.

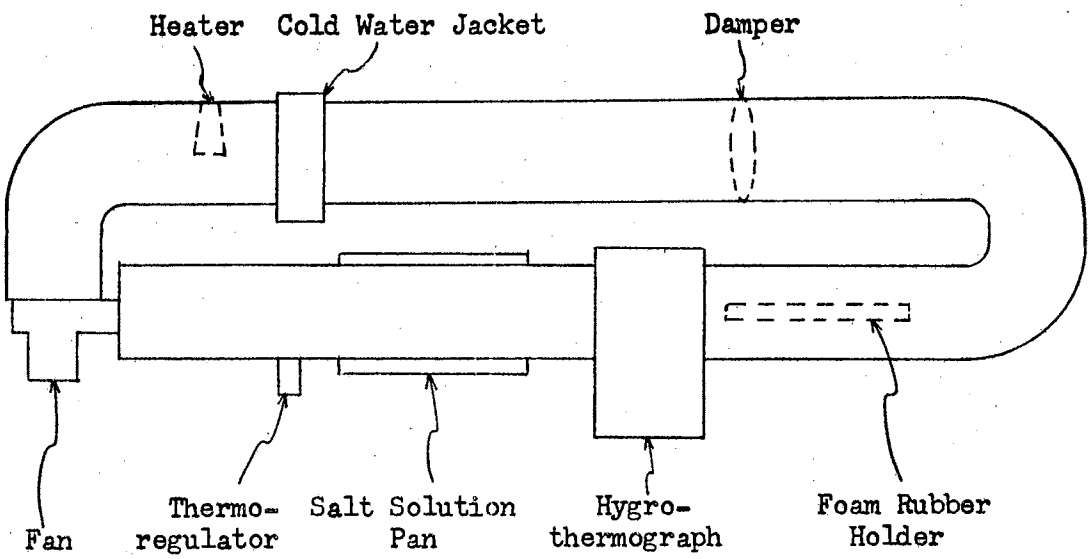

Fig. 22. Schematic of Top Duct and Components.

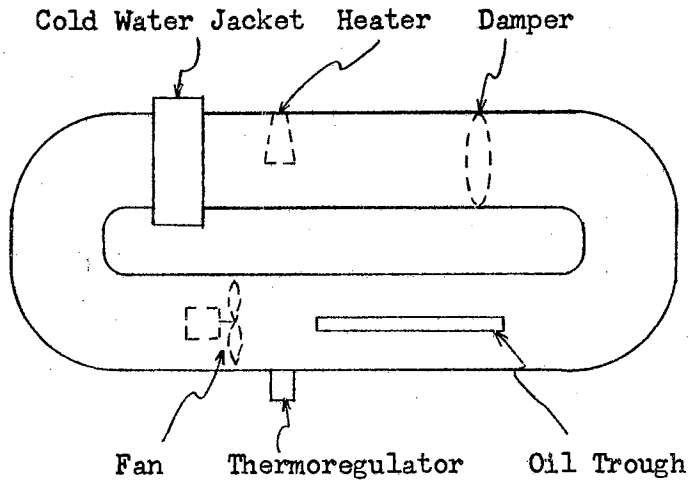

Fig. 23. Schematic of Bottom Duct and Components.

output. The heat sink was a cold water jacket. A centrifugal pump circulated water through one or both water jackets, and then over the cooling coils of an air conditioner. The amount of cooling was controlled by the amount of water circulated in each water jacket.

The temperature of the air in each duct was regulated by turning the heater on and off. The heater was controlled with an electrical relay and a single pole, double throw, bimetallic thermoregulator. The heater controls caused the air temperature to cycle between a minimum and a maximum. The thermoregulator was capable of controlling the air temperature within $\pm 1^{\circ}F$ by carefully balancing the outputs of the heat source and heat sink.

Temperature and Relative Humidity Measurements

The relative humidity of the air in the top duct was continuously recorded on a hygro-thermograph placed inside the top duct. Its relative humidity sensing element was positioned in the air stream. The relative humidity recording component was calibrated with a sling psychrometer.

Other temperatures were recorded on a 12-point, recording potentiometer. Eight thermocouples were used to measure the temperature distribution in one of the drying samples in each test. The thermocouples were threaded through the rock wool insulation adjacent to the drying samples. The thermocouple junctions were imbedded in the corn meal through eight-1/16 in. diameter holes spaced one inch on centers along the length of the drying sample. Two thermocouples sensed the air

temperature surrounding the ducts. One of the two remaining thermocouples sensed the temperature of the oil bath at the bottom of the drying samples and the other sensed the air temperature in the top duct.

Diffusivity Measuring Apparatus

In Chapter III, one of the basic parameters listed in the dimensional analysis was the diffusion coefficient, D. The derivation of an expression for D is followed by a description of the diffusivity measuring apparatus.

Consider the binary gas system of water vapor and air. At a constant molal density, ρ, Fick's First Law (6) defines the diffusion coefficient, D_{va}, in equation (4 - 1).

$$I_v = -D_{va} \frac{d}{dy} (\rho_v) \qquad (4 - 1)$$

where I_v = flux of water vapor with respect to u, lb. moles/hr. ft.^{2}

$u = \frac{N}{\rho}$ = molal average velocity of the air and water vapor in y direction, ft./hr.

N = the molal flux of water vapor, N_v, plus the molal flux of air, N_a, with respect to fixed coordinates in space, lb. moles/ft.^{2} hr.

ρ = the molal density of water vapor, ρ_v, plus the molal density of air, ρ_a, lb. moles/ft.^{3}

D_{va} = diffusion coefficient of water vapor in air, ft.^{2}/hr.

$\frac{d}{dy}(\rho_v)$ = gradient of concentration of water vapor in y direction, lb. moles/ft.^{3}/ft.

The total molal flux of water vapor with respect to fixed coordinates can be expressed as that flux with respect to the molal average velocity plus the flux caused by the bulk flow related to u or

$$N_v = I_v + N \rho_v/\rho \qquad (4 - 2)$$

The last term in equation (4 - 2) is neglected in many cases when ρ_v/ρ is small. In this derivation, however, it is retained. For the diffusion of water vapor in stagnant air, $N_a = 0$, so that $N = N_v$. Then equation (4 - 2) reduces to equation (4 - 3).

$$N_v = I_v + N_v \rho_v/\rho \qquad (4 - 3)$$

$$\text{or } N_v = \frac{I_v}{1 - \rho_v/\rho} \qquad (4 - 4)$$

Substituting equation (4 - 1) into equation (4 - 4) gives

$$N_v = \frac{-D_{va} \frac{d\rho_v}{dy}}{1 - \rho_v/\rho} \qquad (4 - 5)$$

Equation (4 - 5) can be written in terms of partial pressures since

$$P_v + P_a = P$$

and

$$\frac{\rho_v}{\rho} = \frac{P_v}{P}$$

where P_v = partial pressure of water vapor, atm.

P_a = partial pressure of air, atm.

P = total pressure, atm.

For constant molal density and total pressure, equation (4 - 5) can be written

$$N_v = \frac{-D_{va}\,\rho\,\frac{dP_v}{dy}}{P - P_v} \qquad (4 - 6)$$

If $P_v = P_{vo}$ at $y = 0$ and $P_v = P_{vL}$ at $y = L$, then equation (4 - 6) can be integrated from 0 to L to give

$$D_{va} = \frac{N_v L}{\rho \ln\left[\frac{P-P_{vL}}{P-P_{vo}}\right]} = \frac{N_v LRT}{P \ln\left[\frac{P-P_{vL}}{P-P_{vo}}\right]} \qquad (4 - 7)$$

where $\rho = P/RT$ by ideal gas law

R = universal gas constant, 0.73 $\frac{\text{atm. ft.}^3}{\text{lb. mole } {}^\circ\text{R}}$

T = absolute temperature, $^\circ$R

If the binary gas system of water vapor and air is replaced by a system of water vapor in the air voids of corn meal, D is also defined by equation (4 - 7). However, D would be expected to be less than D_{va} since the water vapor flux, N_v, through the tortuous air paths of corn meal would be less than that through stagnant air without obstructions.

D and D_{va} were measured in this investigation. The measurement of D_{va} was not necessary in the experiment. However, comparing the measured values of D_{va} with those in the literature provided a check on the methods and apparatus.

The apparatus is shown in Fig. 24. It consisted of two glass jars, two intact 50-ml. Florence flasks and four modified 50-ml. Florence flasks. Three of the flasks were suspended from the lid of each jar. Within each jar, two modified flasks were used to determine D and the remaining flask was used to determine D_{va}.

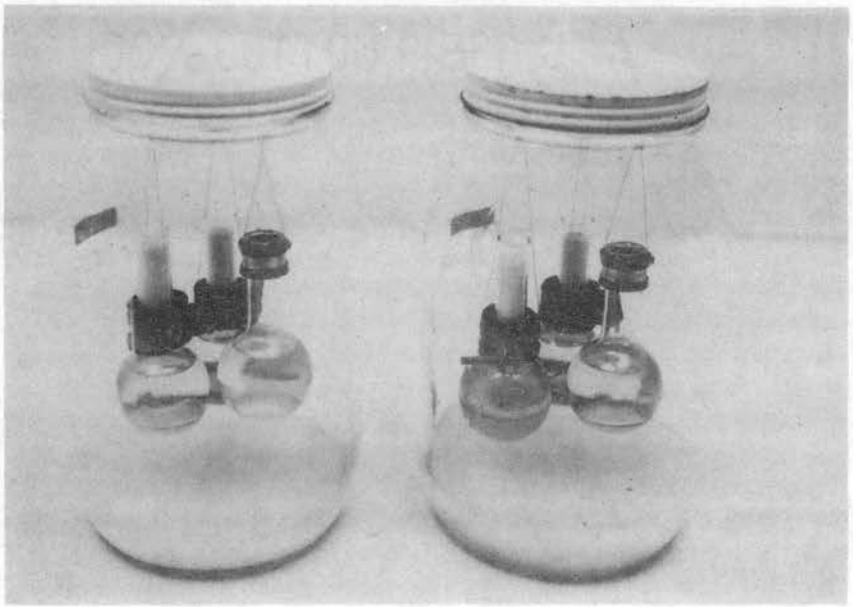

Fig. 24. Diffusivity Measuring Apparatus.

The principal components of the flasks are shown in Fig. 25. The partial pressure, P_{vo}, was maintained at the bottom of the flask neck by the salt solution in the flask bulb. At the top of the flask neck, P_{vL} was maintained by the salt solution in the glass jar. Water vapor diffused through the flask neck from y = 0 to y = L.

The necks of the two intact flasks were two inches long and 0.567 in. ID. The other flasks were modified by replacing the necks with glass tubes two inches long and approximately 0.605 in. ID. The necks were connected to the bulbs with a short length of thick-wall rubber tubing as shown in Fig. 24. A 100-mesh copper screen was cemented to the bottom of each neck to prevent the corn meal from falling into the salt solution in the flask bulb.

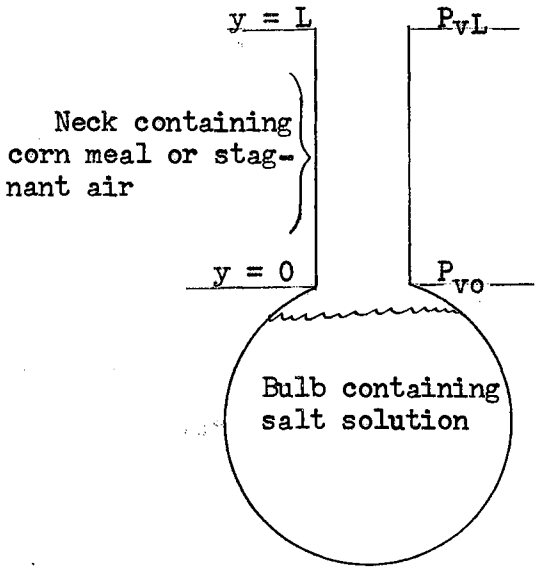

Fig. 25. Schematic of Flask.

CHAPTER V

EXPERIMENTAL PROCEDURE

In Chapter III, basic parameters pertinent to the drying investigation were defined. The parameters were combined to form independent Pi terms as variables for the experiment.

One objective of the study was to experimentally determine the effect of a temperature gradient on the moisture distribution during the drying process. This effect was evaluated at different Π_2 values.

To accomplish this objective, the dependent variables, Π_1 and Π_2, were observed simultaneously. Π_1 was observed as functions of Π_5, Π_7, Π_8, Π_9, and Π_{10}. Π_2 was observed as functions of Π_5, Π_8, Π_9, and Π_{10}. Π_3, Π_4, and Π_6 were held constant to restrict the scope of the study. A general prediction equation expressing Π_1 at different levels of Π_7 yielded the moisture distribution. Similarly, a general prediction equation for Π_2 gave the water lost by the solid.

The experimental schedule is shown in TABLE II. The tests were conducted in the order presented in TABLE II. Only one replication was made on each test.

The levels of the independent Pi terms were determined in

TABLE II

EXPERIMENTAL SCHEDULE

Test No.	Observed	Π_5	Π_7	Π_8	Π_9	Π_{10}
1	Π_1, Π_2	1.000	.03125 .4375 .09375 .5625 .15625 .6875 .21875 .8125 .3125 .9375	25.4 29.8 35.0	20.92	.50
2	Π_1, Π_2	1.000	"	30.1	8.37 16.74 25.11 33.48	.50
3	Π_1	1.000	"	29.9	20.92	.50
4	Π_1, Π_2	0.966 1.000* 1.040	"	29.9	20.92	.50
5	Π_1, Π_2	1.000	"	29.7	20.92	.24 .50* .70

* Used data from test 1, $\Pi_8 = 29.8$

Value of the Pi terms held constant were:

$\Pi_3 = 2.3$

$\Pi_4 = 18$

$\Pi_6 = 0.002434$

preliminary tests. The principal considerations in the selection of these levels were the limitations of methods and equipment and the characteristics of the corn meal.

$\prod_1$ was observed at all levels of $\prod_7$ in tests 1, 2, 4, and 5. These observations were felt necessary because an optimum constant value for $\prod_7$ in these tests was not known prior to the experiment.

Tests 4 and 5 were conducted at only two levels of $\prod_5$ and $\prod_{10}$, respectively. As indicated in TABLE II, data from test 1, $\prod_8 = 29.4$, were used for intermediate levels of $\prod_5$ and $\prod_{10}$ in tests 4 and 5.

$\prod_8$ was not held at some constant value in tests 2, 4, and 5. However, for the purpose of evaluating component equations, $\prod_8$ was assumed constant at 30.

Test Procedure

A procedure for setting up the equipment, preparing the drying samples, and recording the data was essential for consistent results. The steps (numbered for reference) followed in conducting a test were:

1. Prepare, mark, and weigh glass tubes for drying samples.
2. Add distilled water to corn meal to obtain moisture content, M_i.
3. Thoroughly mix corn meal and place in sealed container in cold storage at 40°F for 24 hours.
4. Remove corn meal from cold storage.

5. Seal with paraffin 1/16 in. diameter holes along length of glass tube for check sample.
6. If test number is 2, proceed to step 8. If test number is not 2, proceed to step 7.
7. Prepare drying samples by filling check sample glass tube and six other glass tubes with corn meal. Screen corn meal through 15 mesh sieves. Proceed to step 9.
8. Prepare drying samples by filling check sample glass tube and 15 other glass tubes with corn meal. Screen corn meal through 25 mesh sieves.
9. Seal the open end of the tubes with masking tape and place in cold storage at 40°F for 24 hours.
10. Turn on fans, heat sources, and heat sinks of drying apparatus.
11. Adjust thermoregulators on top and bottom ducts for temperatures T_o and T_L.
12. Adjust temperature surrounding drying apparatus at $(T_o + T_L)/2$.
13. Add salt solution to plastic pan to obtain desired relative humidity in top duct.
14. Turn on potentiometer and hygrothermograph.
15. Remove corn meal samples from cold storage and subject them to room temperature for one hour.
16. Conduct steps 17 through 22 concurrently with steps 23 through 42.
17. Select three samples at random.

18. Along the length of each sample, divide the corn meal into eight equal parts and pour into weighed metal containers.
19. Weigh and record total weight of corn meal and metal containers.
20. Place corn meal and metal containers in forced-draft oven at 212°F for 24 hours.
21. Remove corn meal and metal containers from oven and allow to cool to room temperature in desiccator.
22. Weigh and record total weight of metal containers and dried corn meal.
23. Remove masking tape from open end of samples not selected in step 17.
24. Weigh and record weight of each sample (corn meal plus glass tube).
25. Place weighed samples in drying apparatus.
26. Remove masking tape from open end of check sample and place it in drying apparatus. Insert eight thermocouple junctions into corn meal along length of check sample.
27. Place empty glass tubes in drying apparatus in any positions not occupied by samples.
28. Clamp insulation around samples.
29. Record time and date.
30. If test number is 2, proceed to step 31. If test number is not 2, proceed to step 32.
31. Allow samples to dry for 12 hours. Proceed to step 33.

32. Allow samples to dry 30 hours.
33. Record time and date.
34. Remove insulation around samples and remove three samples from apparatus.
35. If three or more samples remain in apparatus, proceed to step 36. If less than three samples remain in apparatus, proceed to step 37.
36. Replace samples removed in step 34 with empty glass tubes and repeat step 28. Proceed to step 38.
37. Turn off apparatus and recorders.
38. Weigh and record weight of each sample.
39. Divide each sample into ten parts as follows. Between $x/L = 0$ and $x/L = 0.25$, divide corn meal into four one-half inch parts. Between $x/L = 0.25$ and $x/L = 1.0$, divide corn meal into six one-inch parts.
40. Pour each part into weighed metal container.
41. Repeat steps 19 through 22.
42. If test number is 2, repeat steps 33 through 41 at 24, 36, and 48 hours of elapsed drying time. If test number is not 2, end of test.

Procedure for Evaluation of Pi Terms

Π_3, Π_4, and Π_6 were held constant in the study. Π_4 was the molecular weight of water or 18. Π_3 was assumed to be approximately 2.3,

the value of n for shelled corn (18) at 541°R. Since T_o was 541°R for all tests, the value of Π_6 could be determined by knowing k. Approximately 4.5×10^{-6} $^oR^{-1}$ was taken as the value of k for shelled corn (18) at 541°R, yielding Π_6 as 0.002434.

To evaluate Π_5, temperatures were taken from the strip chart of the recording potentiometer. T_o was the temperature of the air in the top duct. The temperature sensed by the thermocouple nearest the sealed end of the check sample was T_L. Although T_o and T_L were not held constant during the tests, the thermoregulators were set so that the two temperatures cycled about their assumed values. The variation in temperature was approximately $\pm 1^oF$.

Π_{10} was read from the chart of the hygrothermograph. Its value was not held constant because of the variation in air temperature. However, as with Π_5, Π_{10} cycled about its assumed value. Variation from the assumed value was approximately ± 0.02.

Π_7 referred to the position along the sample with respect to its open end. Each sample was eventually divided into ten parts. Each part was of finite length and corresponded to a value of x/L. The distance of the geometrical center of the respective part from the open end determined its value of x, and thus x/L.

The recorded values in steps 19 and 22 of the previous section were used to determine Π_8. Subtraction of the values in step 22 from those in step 19 for each respective part of the sample yielded

the weight of water. Subtraction of the metal container weights for each part from the respective weights in step 22 gave the dry weight of corn meal. Then

$$\frac{\text{weight of water} \times 100}{\text{dry weight of corn meal}} = M_i$$

M_i for a test was then calculated as the average of the M_i values in the samples selected in step 17.

$\prod_1$ was calculated in the same manner as $\prod_8$ by using the values recorded in step 41. The individual values of M_x were preserved to correspond with values of x/L.

The weight of water lost by a sample was the numerator used to calculate its R value or $\prod_2$. This weight was obtained by subtracting the values in step 38 from those in step 24. Subtraction of the weights of the glass tube from its respective weight in step 24 yielded the weight of the wet corn meal in the sample. The dry weight of the corn meal was determined by assuming its initial moisture content at M_i. The weight of water lost by a sample divided by the dry corn meal weight of a sample was its R value.

The most difficult parameter to determine in $\prod_9$ was D. It was measured under steady state conditions. D_{va} was also measured as a check on the methods and apparatus.

Diffusion coefficients are often dependent on vapor pressure. Because of this, tests were conducted to measure D and D_{va} at two vapor pressures, P_{vL}. The coefficients were also determined at 70°

and 81°F.

The vapor pressures of saturated potassium acetate and potassium carbonate solutions were assumed as the two values of P_{vL}. The two salt solutions were placed in separate glass jars. A saturated potassium chromate solution developed the vapor pressure, P_{vo}, in each of the flask bulbs.

The diffusivity tests were conducted by first filling the six flask bulbs with a saturated potassium chromate solution. Corn meal at approximately 11% moisture content (dry basis) was poured into the four two-inch necks of the modified flasks. The necks were not completely filled because of corn meal losses resulting from handling. Two modified flasks and one intact flask were suspended in each of the two glass jars.

The flasks were removed from the glass jars for weighing each day. Weights of the two intact flasks were recorded. For each of the four modified flasks, the neck and flask bulb were weighed separately and recorded. It was necessary to weigh the neck since the net transfer of water vapor through the corn meal was desired when the corn meal had reached equilibrium. This usually required two to three days.

D_{va} and D were calculated with equation (4 - 7). N_v was evaluated on a daily basis using the above weight recordings. N_v was the water vapor flux in lb. moles per hour per ft.^{2} of neck cross-sectional area. The water vapor fluxes for determining D_{va} and D involved the

weight changes of the intact flasks and bulbs of the modified flasks, respectively. In equation (4 - 7), L was the length in ft. of corn meal or stagnant air in the neck through which the vapor passed. T was the absolute temperature in degrees Rankine at which the test was conducted. P_{vL} and P_{vo} were the vapor pressures in atmospheres of salt solutions in the glass jars and flask bulbs, respectively. P was assumed as standard pressure or 1 atmosphere.

Data from daily recordings of the test at 81°F were used to calculate an average value of D in $\prod_9$. L in $\prod_9$ was the length of the drying sample in ft. and t was the elapsed drying time in hours.

CHAPTER VI

PRESENTATION AND ANALYSIS OF DATA

Diffusion Coefficient Measurements

Two glass jars contained the flasks for the diffusion coefficient measurements. A and B corresponded to the jars with the potassium acetate and potassium carbonate, respectively. For each jar, subscripts 1, 2, and 3 referred to the two modified flasks with corn meal and the intact flask with stagnant air, respectively.

Raw data and sample calculations are presented in Appendix C. Average diffusion coefficients are shown in TABLE III.

The diffusion coefficients of water vapor in air, D_{va}, are 0.97 and 1.01 ft.^{2}/hr. at 530 and 541°R, respectively (22). These values differ from those determined with flasks A_3 and B_3 in TABLE III by approximately 2%.

D in $\prod_9$ was taken as the average of the values related to A_1, A_2, B_1, and B_2 in TABLE III at 541°R. To the nearest hundreth, D was 0.31 ft.^{2}/hr.

The values of D at both temperatures with flasks A_1 and A_2 are higher than those with flasks B_1 and B_2. The vapor pressure differential, $P_{vo} - P_{vL}$, was greatest with flasks A_1 and A_2. D also increased

TABLE III

AVERAGE DIFFUSION COEFFICIENTS, FT.^{2}/HR.

Flask	Temperature, Degrees Rankine 530	541
A_1	0.29^5	0.32^{5*}
A_2	0.29^4	0.33^5
A_3	0.95^4	1.02^5
B_1	0.27^5	0.30^4
B_2	0.26^1	0.28^5
B_3	0.98^5	1.02^5

*Superscript numbers are the number of observations in the average value.

with temperature. This indicates a probable variation in D within the corn meal samples during drying, even though it was assumed constant. However, the data proved valuable in the determination of the form of the prediction equations as influenced by Π_5 and Π_{10}.

Data Relevant to Drying Tests

Appendix D presents the raw data of the initial samples to determine Π_8 in the tests. Raw data used to evaluate Π_1, Π_2, Π_5, and Π_9 are shown in Appendix E with Π_7 and Π_{10} given under their respective headings. No data are shown in Appendix E for test 3 of the

experimental schedule. Instead, the 10 levels of Π_7 are presented at all levels in tests 1, 2, 4, and 5.

It should also be noted in both Appendixes that no data exist for the intermediate levels in tests 4 and 5. In these two cases, the data from test 1, $\Pi_8 = 29.8$, were used.

For $\Pi_5 = 1.040$ in test 4 in both Appendixes, data are presented for $\Pi_8 = 26.5$, 31.1, and 36.3. Since none of these values of Π_8 were reasonably close to 30.0, the value at which Π_8 was supposed to be held constant, data sets for Π_1 and Π_2 were interpolated at 30.0 by using the data sets corresponding to $\Pi_8 = 26.5$ and 31.1.

Finally, no data are presented on temperature gradients in the samples in test 4. The temperature recordings on the strip chart of the recording potentiometer indicated that for $\Pi_5 = .966$ and 1.040, the temperature gradients were approximately linear.

Component Equations

Component equations describe the apparent relationship between one independent and one dependent variable. The determination of a component equation requires that all but one independent variable be held constant while observing the dependent variable. In addition when an independent variable is held constant, it should always be the same value.

Since Π_7 was varied in all tests, component equations describing

Π_1 required the selection of the same value of Π_7 in tests 1, 2, 4, and 5. After studying the data for Π_1 vs. Π_7, Π_7 was chosen as 0.15625 because it gave a measurable variation in Π_1 between each of the levels of the independent Pi terms.

Regression analyses were made on the experimental data relating Π_1 and Π_2 and the independent pi terms. Four models of equations were tested for best fit to the data with a computer program using the least-squares method. The models were:

1. $y = a + bx$
2. $y = c + dx + fx^2$
3. $\ln(y) = \ln(g) + h\ln(x)$
4. $\ln(y) = \ln(k) + qx$

where y = dependent Pi term

x = independent Pi term

a, b, c, d, f, g, h, k, q = constants

Model 1 gave the best fit for Π_1 vs. Π_5 and Π_8, and Π_2 vs. Π_5, Π_8, Π_9, and Π_{10}. The remaining relationships, Π_1 vs. Π_7, Π_9, and Π_{10}, fitted model 2 best.

The curves of the component equations and the experimental data are plotted in Figs. 26, 27, 28, 29, 30, 31, 32, 33, and 34. Listed below each curve are the component equation, the coefficient of determination, r^2, and the average values of the independent Pi terms held constant. The coefficient of determination (42) is the proportion

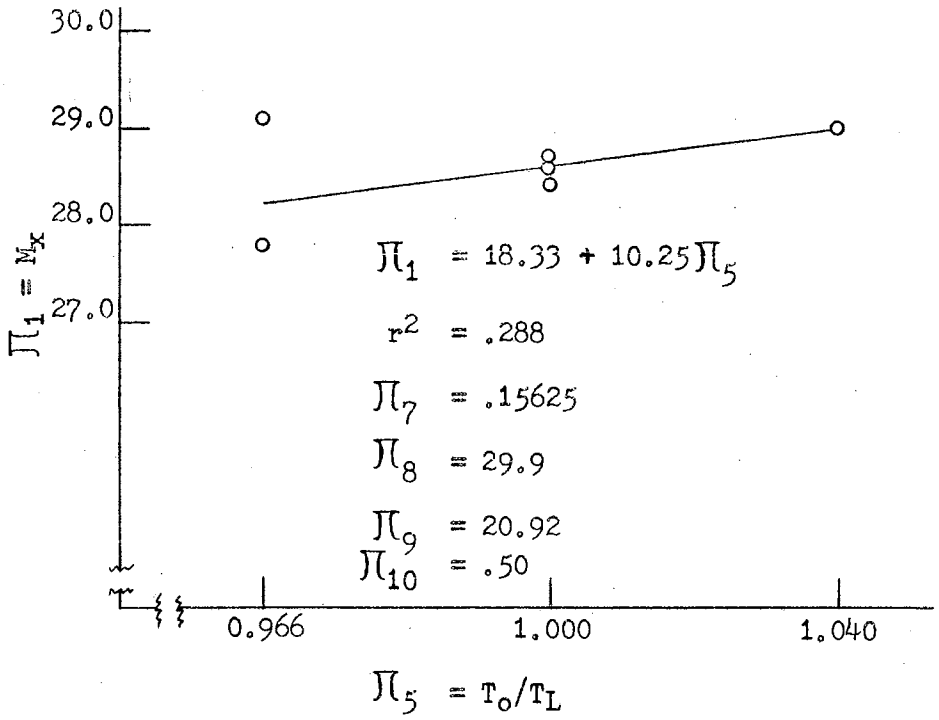

Fig. 26. Π_1 versus Π_5

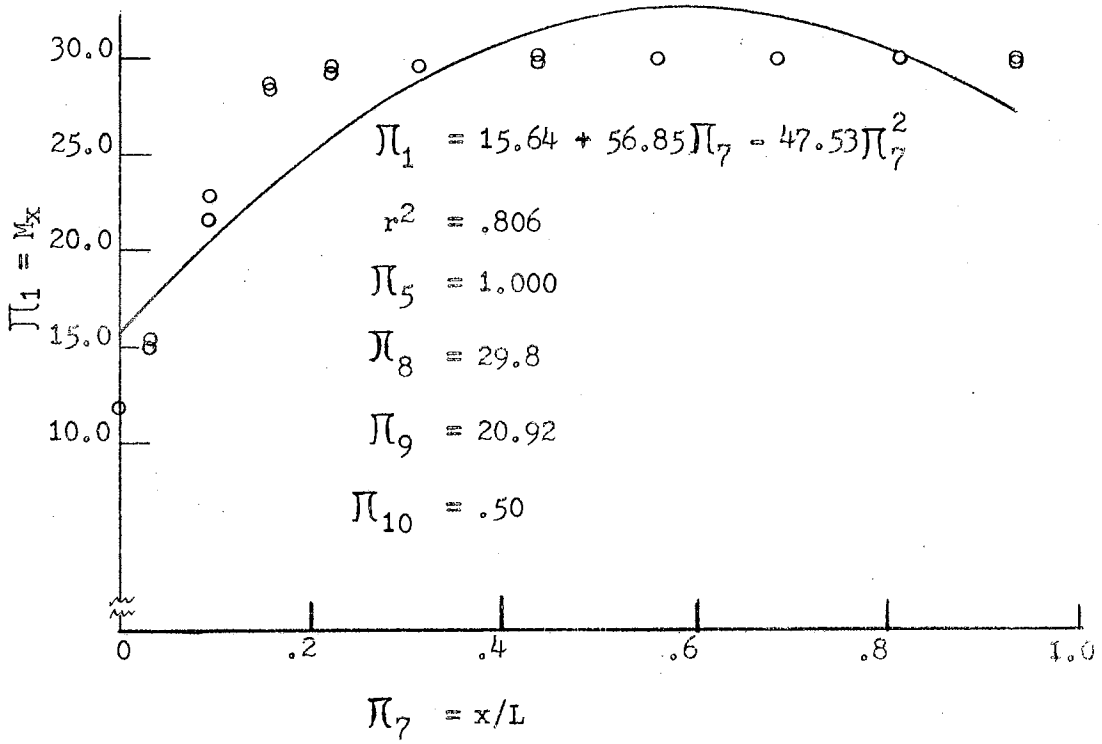

Fig. 27. Π_1 versus Π_7

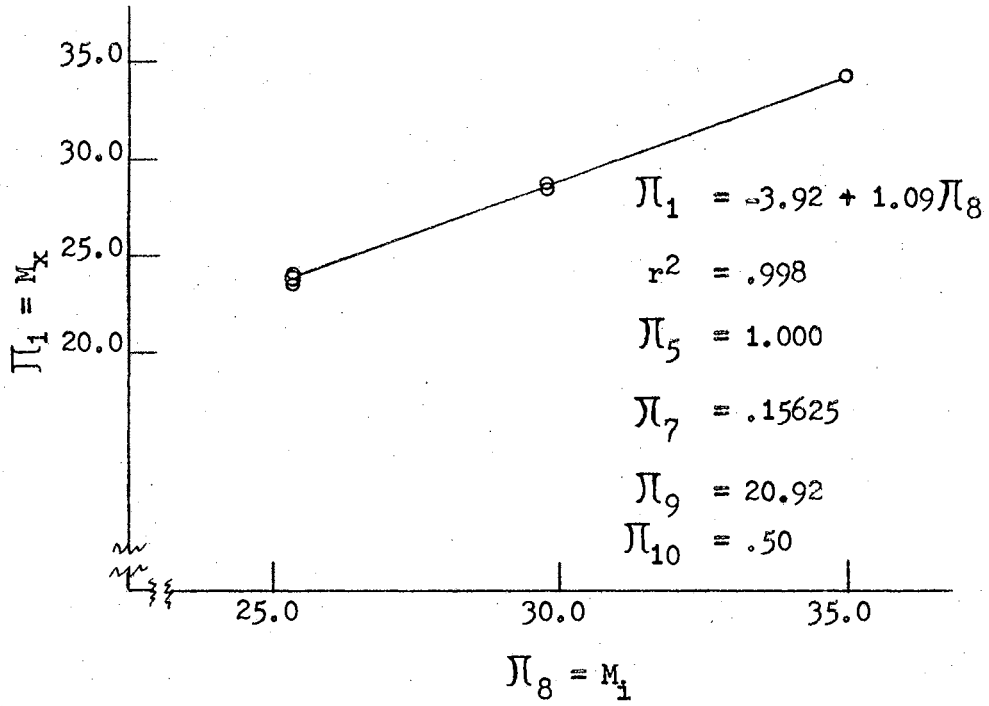

Fig. 28. Π_1 versus Π_8

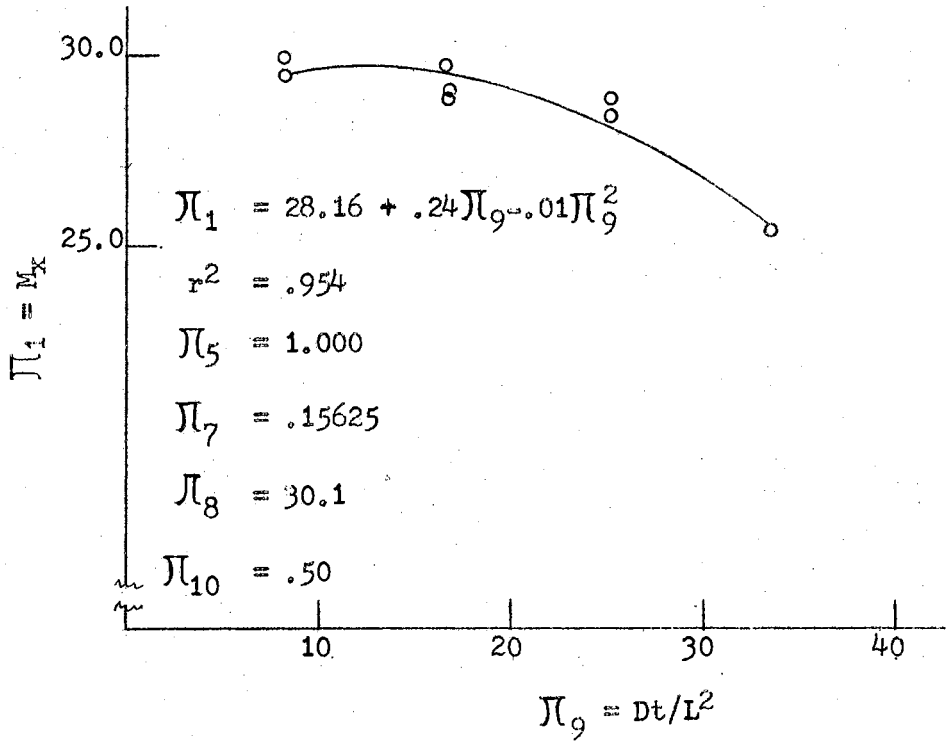

Fig. 29. Π_1 versus Π_9

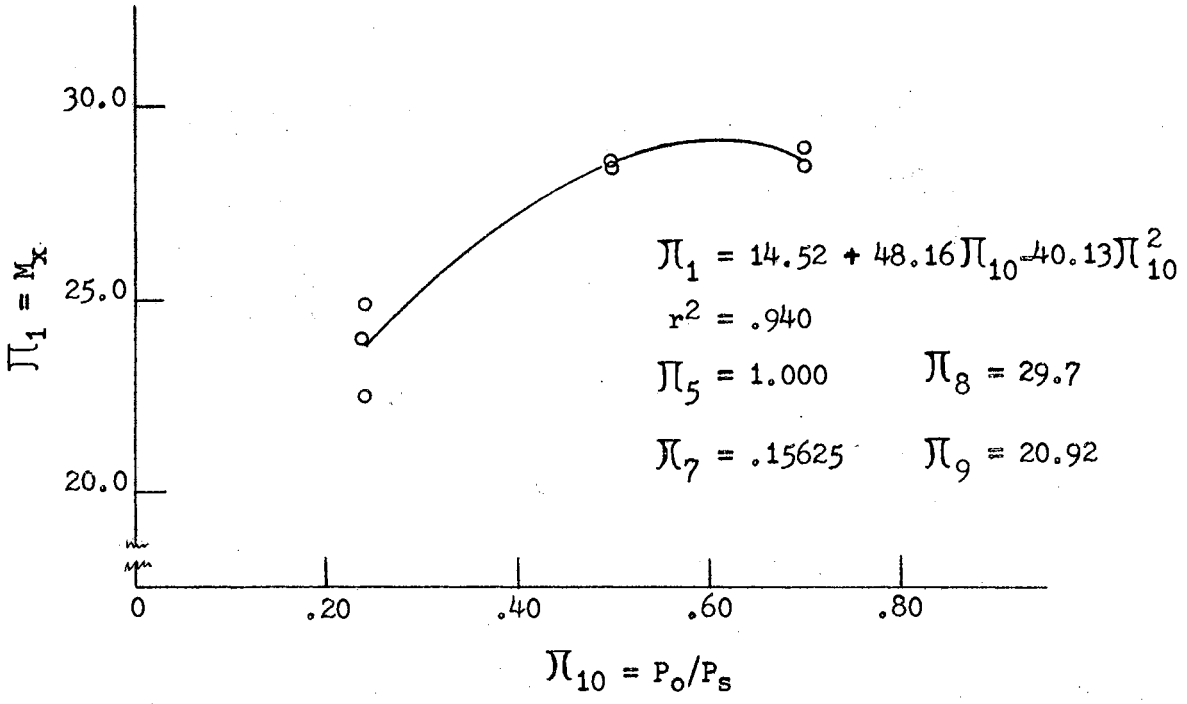

Fig. 30. Π_1 versus Π_{10}

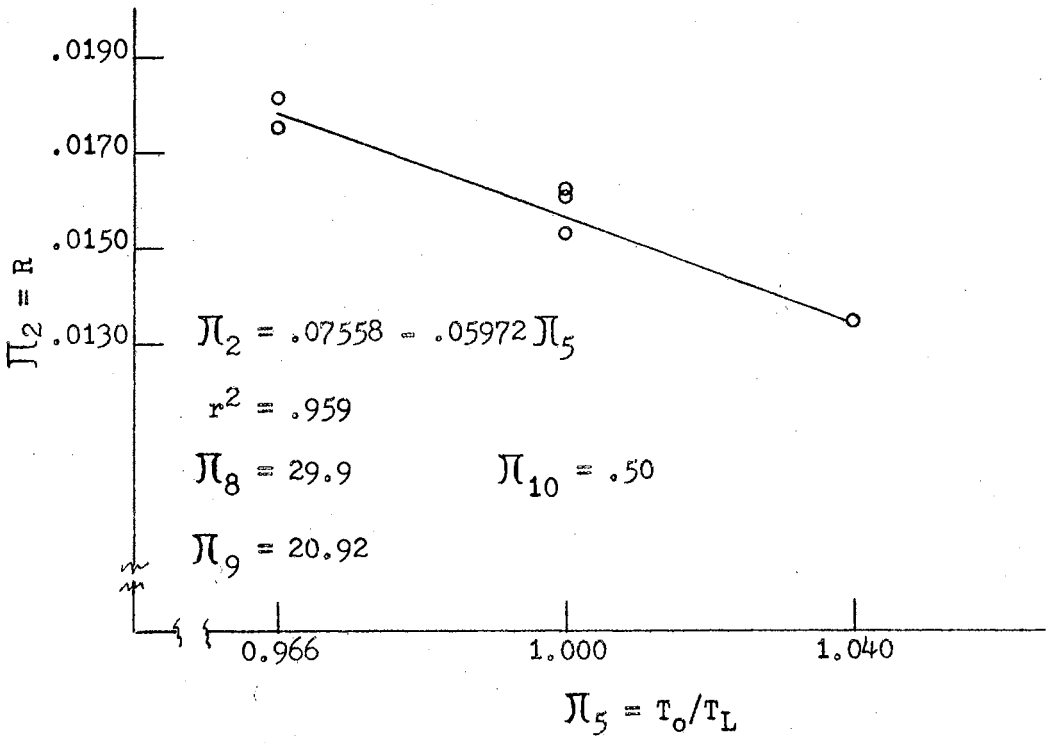

Fig. 31. Π_2 versus Π_5

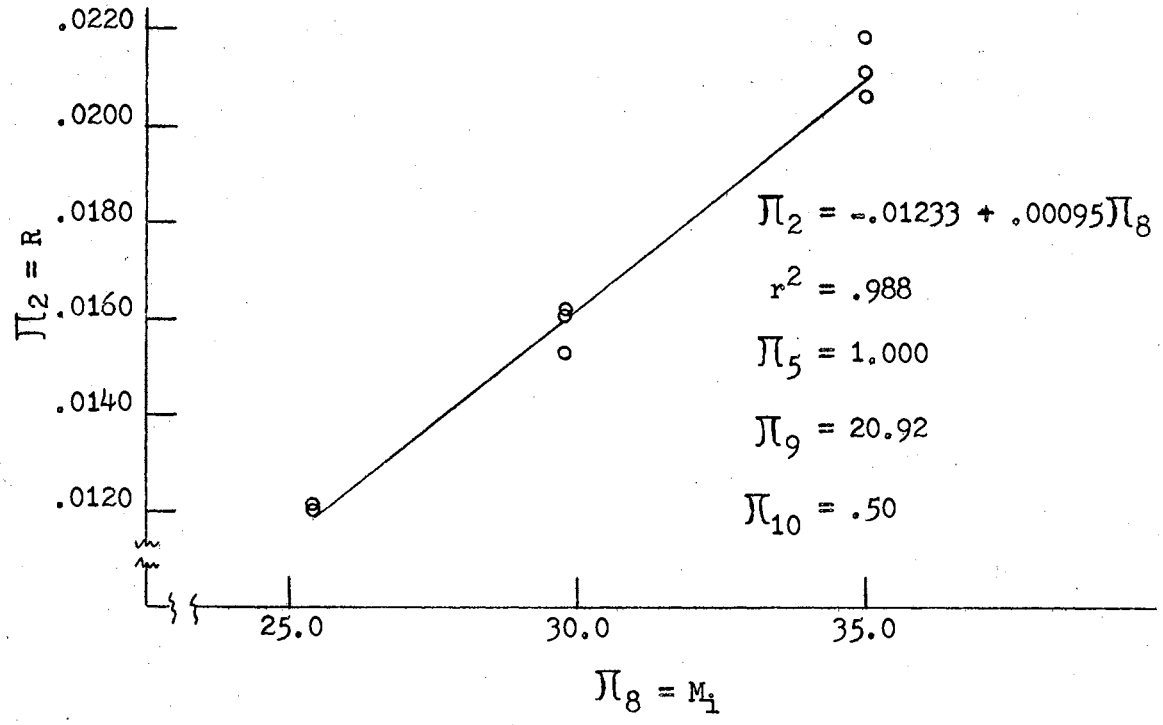

Fig. 32. Π_2 versus Π_8

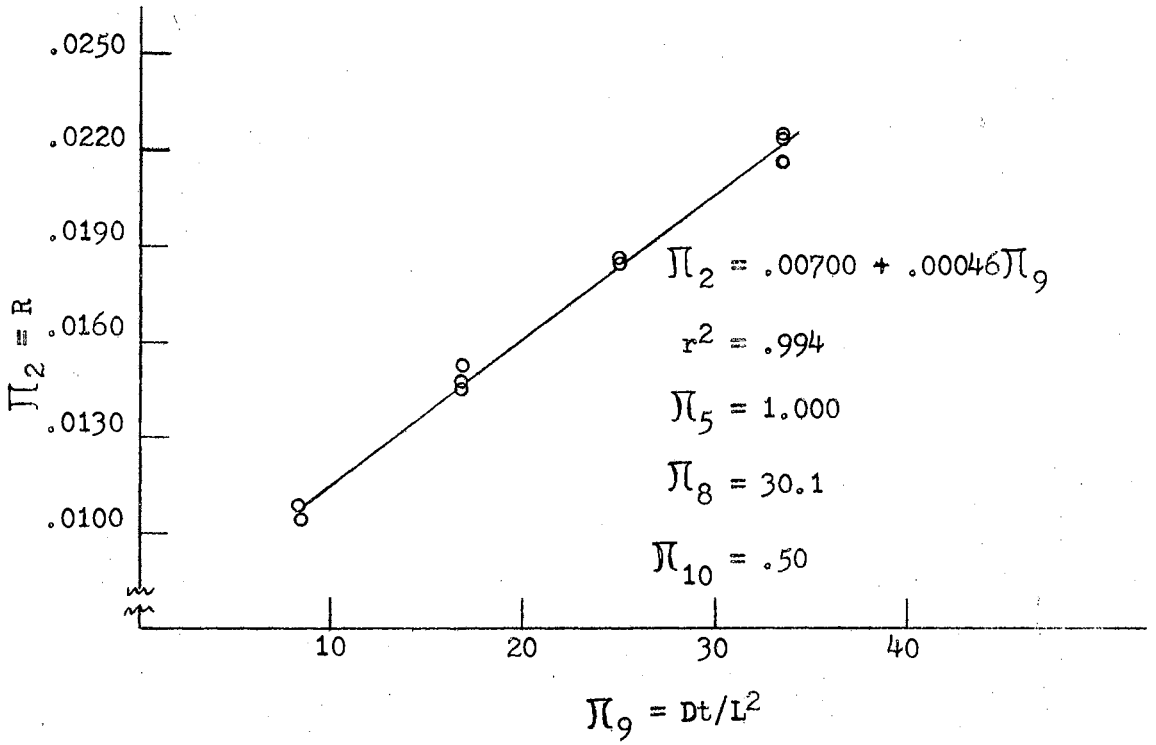

Fig. 33. Π_2 versus Π_9

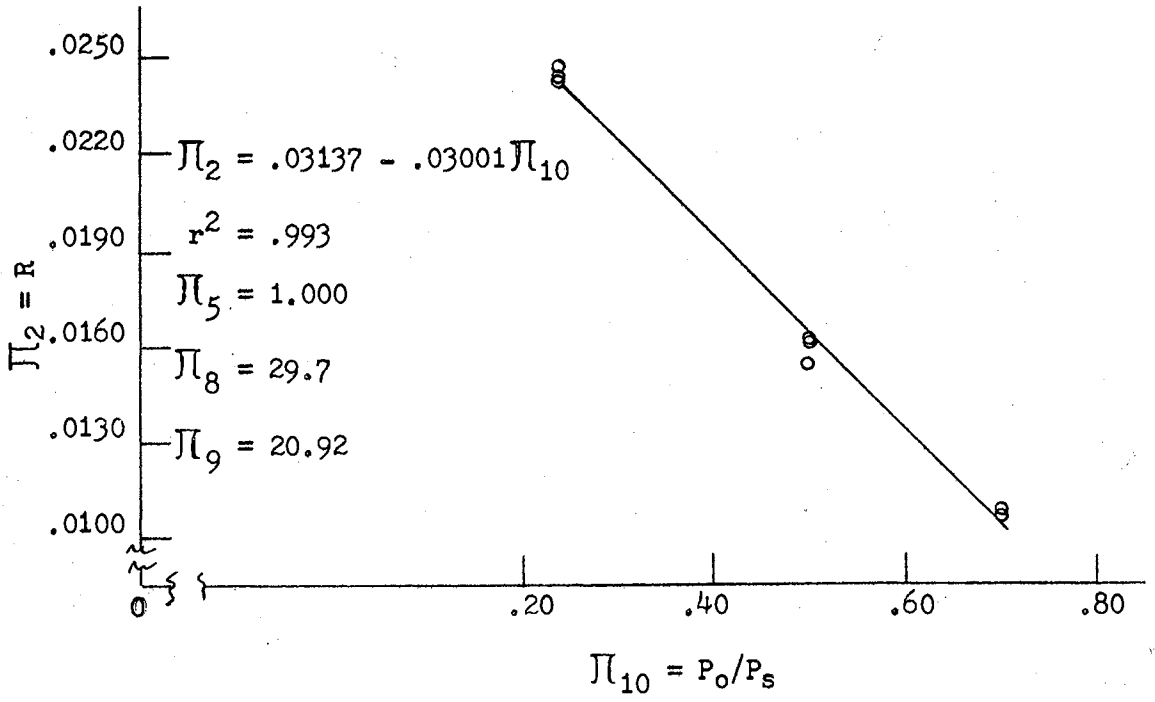

Fig. 34. Π_2 versus Π_{10}

of the total sum of squares that is attributable to the independent Pi term.

Analysis of Initial Samples

The initial moisture content was determined at eight positions along the length of each initial sample. These values were averaged for each sample to the nearest .1 of one percent. Π_8 for a given test was then taken as the average of the sample averages. For any level in a particular test, uniform moisture distributions and the same initial moisture content were desired in all samples.

The samples for each test were analyzed statistically. Each

sample was a treatment. The eight values of moisture content in each sample were treated as eight subsamples. It was hypothesized that the variance between the moisture content averages of samples or treatments was not significant as compared to variance between moisture content values at the positions in the samples. The criterion for significance was the F test.

The results are summarized in TABLE IV. At the .05 level of significance, the hypothesis was false for half the samples. This implied that the average moisture content in these samples was not the same. The average difference between the lowest and highest values of the significant means is 0.3. The method of weighing to determine these sample means was accurate to only $\pm$0.1. Variations of 0.1% in the moisture content of the prepared corn meal could have resulted in the observed difference in the sample means. An example of the moisture distributions in the initial samples is shown in TABLE V for $\Pi_8 = 25.4$ in test 1.

Analysis of Π_1 in Dried Samples

Π_1 was observed at the ten levels of Π_7 in all tests. Statistical analyses of the moisture distributions, Π_1 vs. Π_7, were made. First, at each level of Π_5, Π_8, Π_9, and Π_{10}, sample distributions were compared. Second, in each test, the sample distributions at each Pi term level were pooled as an average, and the average sample distributions were compared.

TABLE IV

STATISTICAL ANALYSIS SUMMARY OF Π_8
IN INITIAL SAMPLES

Test No	No of Pi Term	Level of Pi Term	No of Samples	Sample Means	F
1	8	25.4	3	25.2, 25.5, 25.6	4.42*
1	8	29.8	2	29.7, 29.9	4.00 NS
1	8	35.0	2	34.7, 35.2	5.15*
2	9	ALL	3	29.9, 30.1, 30.3	14.1**
4	5	.0966	3	29.8, 29.9, 30.0	9.34**
4	5	1.040	3	26.5, 26.5, 26.6	0.81 NS
4	5	1.040	3	31.0, 31.0, 31.2	1.95 NS
4	5	1.040	3	36.2, 36.3, 36.4	0.60 NS
5	10	0.24	3	29.5, 29.6, 29.7	7.73**
5	10	0.70	3	29.7, 09.8, 29.9	0.70 NS

NS - Not significant at .05 level

* - Significant at .05 level

** - Significant at .01 level

In the first analysis, each sample distribution was a treatment. Then, at each Pi term level, Π_1 at the respective levels of Π_7 for all samples was averaged. These average distributions were treatments in

TABLE V

MOISTURE CONTENT AS FUNCTION OF POSITION IN INITIAL SAMPLES FOR $\Pi_8 = 25.4$ IN TEST 1

Position x/L	Mean of Sample 25.2	25.5	25.6
.0625	24.8	25.3	25.7
.1875	24.2	25.6	25.5
.3125	25.6	25.6	25.6
.4375	25.1	25.5	25.6
.5625	25.3	25.4	25.4
.6875	25.6	25.7	25.8
.8125	25.5	25.6	25.7
.9375	25.3	25.3	25.5

the second analysis. In both analyses, Π_1 at positions along the samples or levels of Π_7 were treated as blocks. Thus, the total sum of squares in both analyses included treatment, blocks, and error sums of squares.

In all analyses, the F value obtained by dividing the variance of blocks by the variance of error was greater than 25.0 and highly significant. This indicated a significant change of moisture content with position along the sample.

The results of comparing the variance of samples in the first

analysis and the variance of error are summarized in TABLE VI. Five F values are significant at the .05 level. Difference in initial moisture contents accounted for some of this variation. F values not significant supported the assumption that the sample distributions were identical.

In the second analysis, the variance of average sample distributions at Pi term levels was compared with the variance of error. The results are summarized in TABLE VII. The statistical inference of the two significant F values is that the values of Π_1 vs. Π_7 were in general different at the chosen levels of Pi terms. The two F values which are not significant indicated no difference between average moisture distributions at the Pi term levels in tests 2 and 5. However, a possible explanation for this might be that a large percentage of the Π_1 values changed negligibly with Pi term levels, thus masking the change of the remaining Π_1 values. The data from test 5 are presented in TABLE VIII to illustrate this point. For x/L greater than .15625, the average difference between Π_1 at successive levels of Π_{10} was 0.2. For x/L less than .21875, the average difference was 3.6.

Analysis of Π_2 in Dried Samples

One value of Π_2 existed for each dried sample. A statistical analysis was made for each test in which a treatment was the Π_2 values at each Pi term level. The remaining variation between Π_2 values

TABLE VI

STATISTICAL ANALYSIS SUMMARY OF $\prod_1$ AMONG SAMPLES AT LEVELS OF PI TERMS

Test No	No of Pi Term	Level of Pi Term	Initial Moisture Content	No of Samples	F
1	8	25.4	25.4	3	.68 NS
1	8	29.8	29.8	3	1.30 NS
1	8	35.0	35.0	3	5.49*
2	9	8.37	30.1	2	24.00**
2	9	16.74	30.1	3	4.09*
2	9	25.11	30.1	3	3.99*
2	9	33.48	30.1	3	0.48 NS
4	5	0.966	29.9	3	0.15 NS
4	5	1.040	26.5	3	3.42 NS
4	5	1.040	31.1	3	0.43 NS
4	5	1.040	36.3	3	2.80 NS
5	10	0.24	29.6	3	6.90**
5	10	0.70	29.8	3	1.36 NS

NS - Not significant at .05 level

* - Significant at .05 level

** - Significant at .01 level

TABLE VII

STATISTICAL ANALYSIS SUMMARY OF Π_1 AMONG PI TERM LEVELS IN EACH TEST

Test No	No of Pi Term	No of Levels	F
1	8	3	67.41**
2	9	4	0.55 NS
4	5	3	5.17*
5	10	3	2.29 NS

NS = Not significant at .05 level

* = Significant at .05 level

** = Significant at .01 level

TABLE VIII

AVERAGE VALUES OF Π_1 IN TEST 5

Position x/L	Level of Π_{10} 0.24	0.50	0.70
.03125	10.9	15.1	17.9
.09375	16.2	21.9	24.0
.15625	23.8	28.6	28.8
.21875	29.0	29.3	29.5
.31250	29.4	29.5	29.8
.43750	29.5	29.9	29.9
.56250	29.5	29.9	29.8
.68750	29.5	29.8	29.8
.81250	29.3	29.8	29.7
.93750	29.5	29.8	29.7

within treatments was pooled as error. An F value was calculated for each test by dividing the variance of treatments by the variance of error. A summary of the F values is presented in TABLE IX. All F values were highly significant.

TABLE IX

STATISTICAL ANALYSIS SUMMARY OF Π_2 AMONG PI TERM LEVELS IN EACH TEST

Test No	No of Pi Term	No of Levels	F
1	8	3	338**
2	9	4	361**
4	5	3	47**
5	10	3	1202**

** - Significant at .01 level

The summaries in TABLES VII and IX are similar in that the dependent variables were compared at different Pi term levels in each test. There appeared to be little doubt that Π_2 was different at each Pi term level in each test. This was not the case for Π_1 vs. Π_7 although Π_2 is entirely dependent on Π_1 vs. Π_7. A possible explanation for this difference follows. Π_2 was one number for each sample to measure the effect of a Pi term level. In contrast, Π_1

was analyzed such that it consisted of ten numbers corresponding to the ten levels of $\prod_7$ per sample, and except for test 1, the majority of the $\prod_1$ values changed negligibly between Pi term levels. This was evidenced by the fact that only three or four of the ten $\prod_1$ values varied markedly from the initial moisture content in tests 2, 4, and 5. Thus the marked change of these three or four $\prod_1$ values, which usually accounted for the change in $\prod_2$, was masked by the remaining $\prod_1$ values.

Prediction Equations

A prediction equation expresses the dependent Pi term as some function of the independent Pi terms. Difficulty is often encountered in determining the nature of the function. As described in Chapter III, Murphy states two possible functions if the component equations meet certain conditions. First, if all component equations plot as straight lines in log-log space, the independent Pi terms can be combined by multiplication. Second, if all component equations plot as straight lines in arithmetic space, the independent Pi terms can be added.

The component equations for $\prod_1$ did not meet either one of the above conditions. Since $\prod_2$ was a linear function of the independent Pi terms, its component equations satisfied the second set of conditions.

The component equations were not used to determine the form of the prediction equations. Instead a form similar to that derived by theory in Chapter III was proposed for Π_1 as follows:

$$\frac{\Pi_1 - (B + A\,\Pi_{10})}{\Pi_8 - (B + A\,\Pi_{10})} = \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{\sin\,(2n-1)(\Pi_7)(\frac{\pi}{2})}{2n-1} \left[\exp(P1)\right] \qquad (6-1)$$

where $P1 = (2n-1)^2\, C(\Pi_9) \left[1 - E(\Pi_5 - 1)\right]$

A, B, C, E, = constants

$B + A\,\Pi_{10}$ is equilibrium moisture content of the corn meal at Π_{10} and T_o in Π_5. For the range of Π_{10} in the tests, .24 to .70, and at $T_o = 541^\circ R$, the equilibrium moisture content of shelled corn is a linear function of Π_{10} (18). A and B were determined as 3.6 and 16.3, respectively. Π_5 was inserted into the expression for P1 because as indicated in TABLE III, the diffusion coefficient, D, changes with temperature.

Theoretically, if equation (6 - 1) yields the proper moisture distribution, Π_1 vs. Π_7, then the prediction equation for Π_2 is

$$\Pi_2 = \frac{1}{100}\int_o^1 \Pi_8\, d(\Pi_7) - \frac{1}{100}\int_o^1 \Pi_1\, d(\Pi_7) \qquad (6-2)$$

or

$$\Pi_2 = G - G(\frac{8}{\pi^2}) \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \left[\exp\,(P1)\right] \qquad (6-3)$$

where $G = \Pi_8 - 3.6 - 16.3\,\Pi_{10}$

In testing equations (6 - 1) and (6 - 3), it was found that a change in Π_{10} did not predict enough change in Π_1 and Π_2. The diffusion coefficient measurements suggested that the diffusion coefficient, D, varied with vapor pressure differential or inversely with Π_{10}.

The second set of prediction equations proposed were as follows:

$$\frac{\Pi_1 - M_e}{\Pi_8 - M_e} = \frac{4}{\pi}\sum_{n=1}^{\infty} \frac{\sin\,(2n-1)(\Pi_7)(\frac{\pi}{2})}{2n-1}\left[\exp\,(P2)\right] \qquad (6 - 4)$$

where $M_e = 3.6 + 16.3\,\Pi_{10}$

and integrating equation (6 - 2) with Π_1 given by equation (6 - 4)

$$\Pi_2 = G - G\,(\frac{8}{\pi^2})\sum_{n=1}^{\infty} \frac{1}{(2n-1)^2}\left[\exp\,(P2)\right] \qquad (6 - 5)$$

where $P2 = P1\left[1-F(\Pi_{10} - .50)\right]$

Comparison of Predicted and Experimental Values

Constants C, E, and F were evaluated so that the predicted values of Π_2 were within 5% of the average experimental values of Π_2. The constant values were:

C = .00073

E = 7.5

F = 1.95

Predicted curves and average experimental points for Π_1 are presented in Figs. 35 through 43. Curve parameters include Π_5, Π_8, Π_9, and Π_{10}. The form of the prediction equation assumes that the moisture flux is proportional to the moisture gradient. The agreement between the curves and experimental points was evidence that this assumption was reasonably good.

Figs. 38 through 41 correspond to test 2. It should be noted that Π_8 is different in each figure. Although Π_8 was determined as 30.1 initially, the samples for Π_9 greater than 8.37 appeared to increase in moisture content. This can be seen by comparing the experimental values of Π_1 for Π_7 greater than .4. Apparently, the volatile constituents of the corn meal increased with time. To make the prediction equation more closely fit the experimental distributions, Π_8 was calculated in each figure as the average of Π_1 for Π_7 greater than .4.

For Π_7 greater than .6, the experimental values of Π_1 are essentially uniform in Figs. 37 through 43. This is not true in Figs. 35 and 36. Fig. 35 shows that the temperature of 560°R in the region at $\Pi_7 = 1$ caused the corn meal to release water vapor. The higher vapor pressure in this region drove the released water vapor to the region between $\Pi_7 = .6$ and $\Pi_7 = .8$. The converse is true in Fig. 36. Water vapor from the region of higher temperature between $\Pi_7 = .6$ and

$\Pi_7 = .8$ moved toward $\Pi_7 = 1$ where the temperature was held at 520°R.

The predicted curves and experimental points for Π_2 are presented in Figs. 44, 45, 46, and 47. Values of the independent Pi terms are indicated. Except for Fig. 45, Π_8 varies with the Pi term on the abscissa. The values indicated were those determined in the experiment and used in the prediction equation. Π_8 in Fig. 46 was determined in the manner previously discussed for Figs. 38 through 41.

The goodness of fit between predicted and experimental values was tested with a linear regression analysis. Predicted and experimental values were treated as dependent and independent variables, respectively. A perfect fit between the two sets of values would yield both the slope of the regression line, b, and the coefficient of determination, r^2, as 1.

The results are summarized in TABLES X and XI. The values of r^2 were all .95 or greater. The t test (42) was used as the criteria to test the hypothesis that the value of b was 1. The hypothesis was true for all values of b at the .01 level of significance.

Predicted Effect of Temperature Gradient on Moisture Transfer and Moisture Distribution

The effect of a temperature gradient on the drying of corn meal was evaluated using equations (6 - 4) and (6 - 5). Moisture distributions, Π_1 vs. Π_7, and Π_2 were calculated at 12 hour intervals up to 72 hours drying time for $\Pi_5 = 1.000$ and .960. Π_8 and Π_{10} were constant

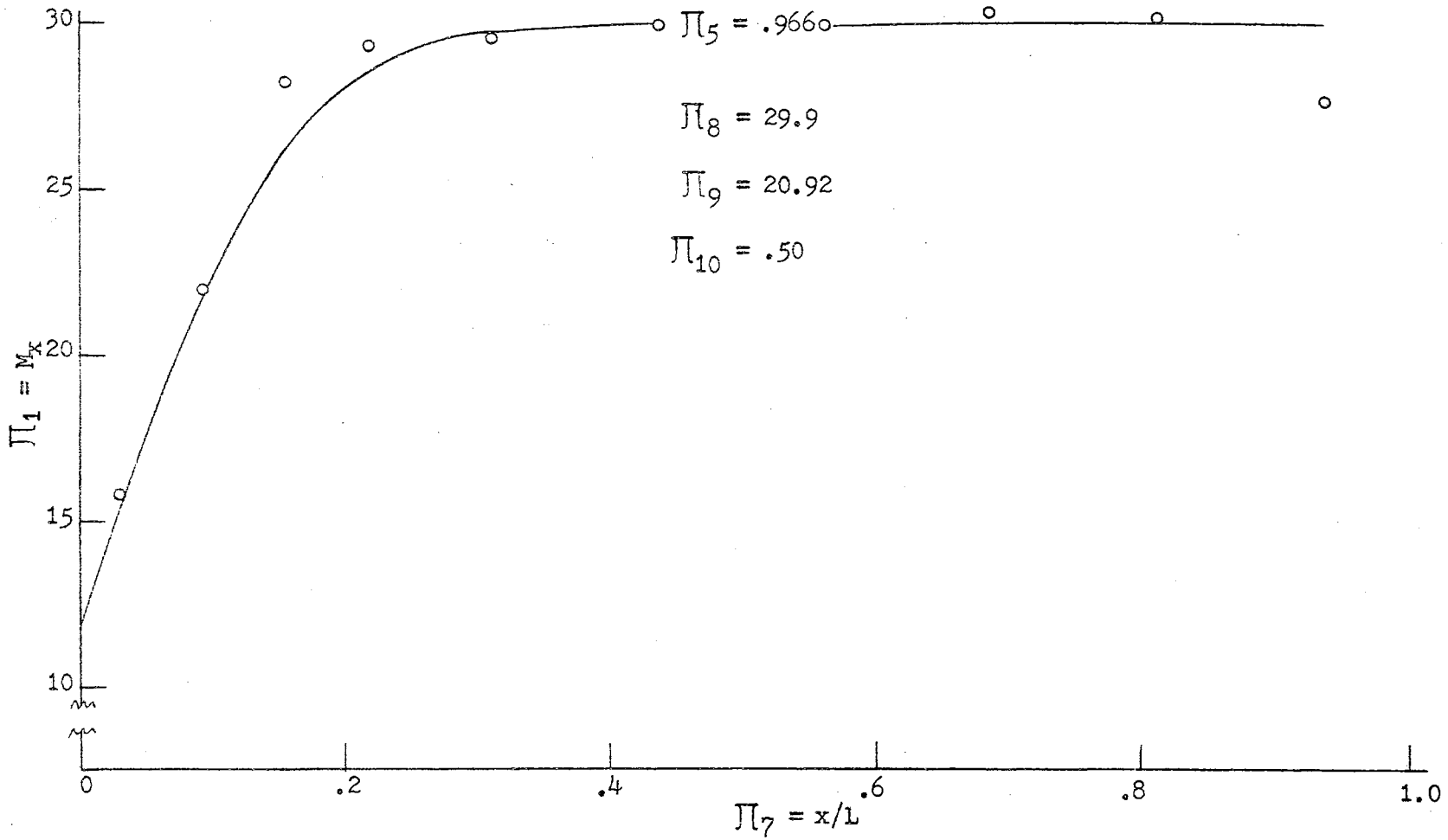

Fig. 35. Π_1 versus Π_7

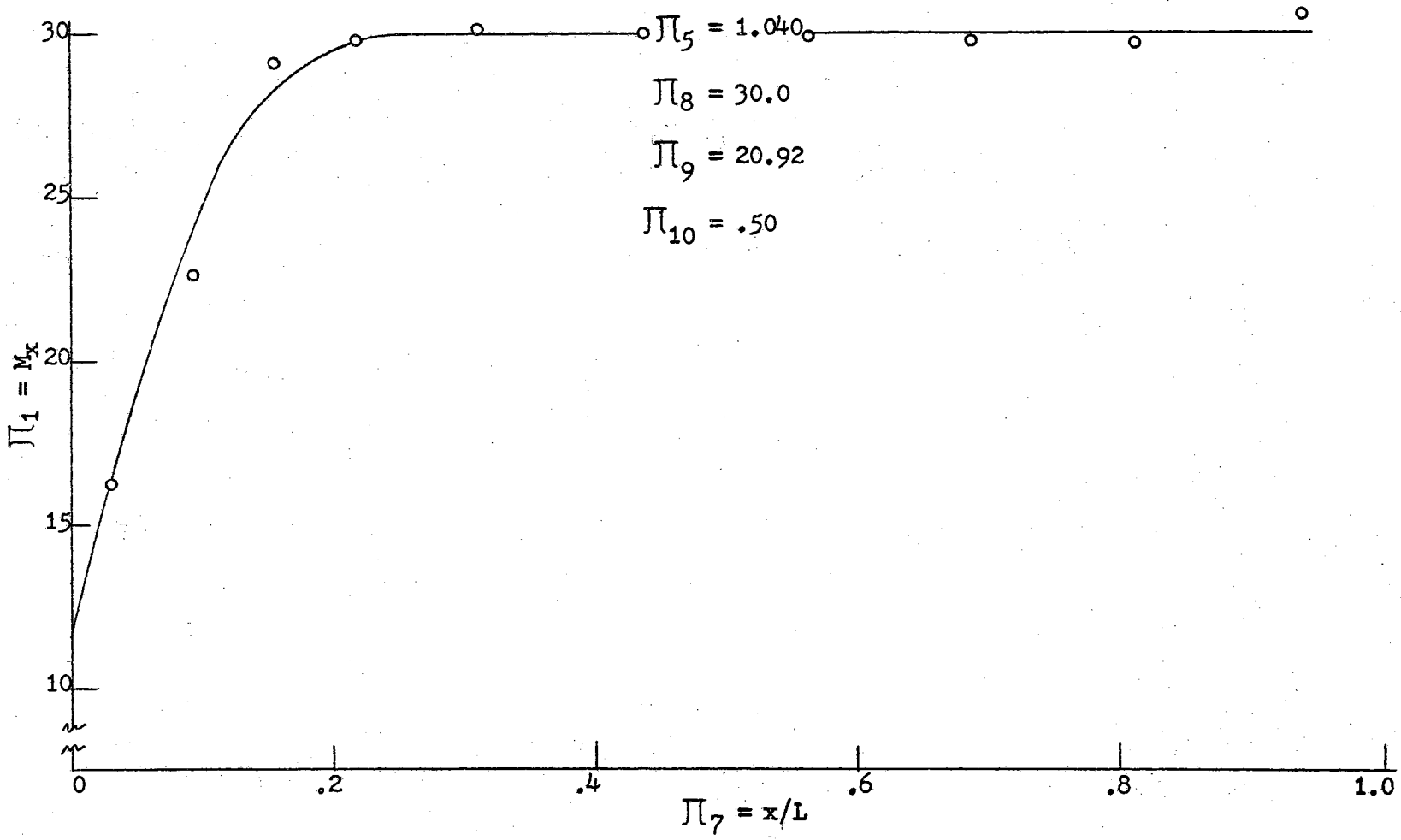

Fig. 36. Π_1 versus Π_7

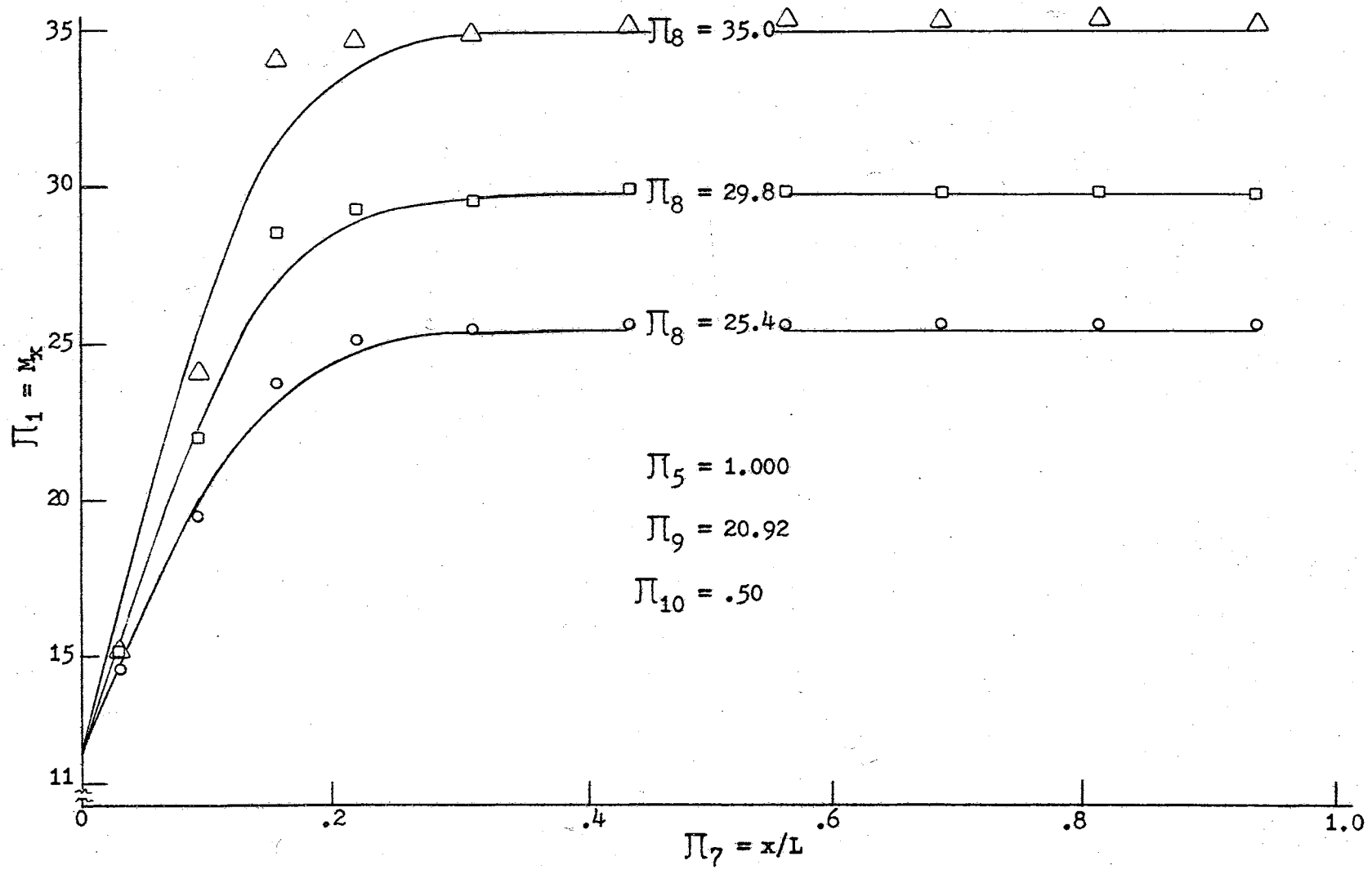

Fig. 37. Π_1 versus Π_7

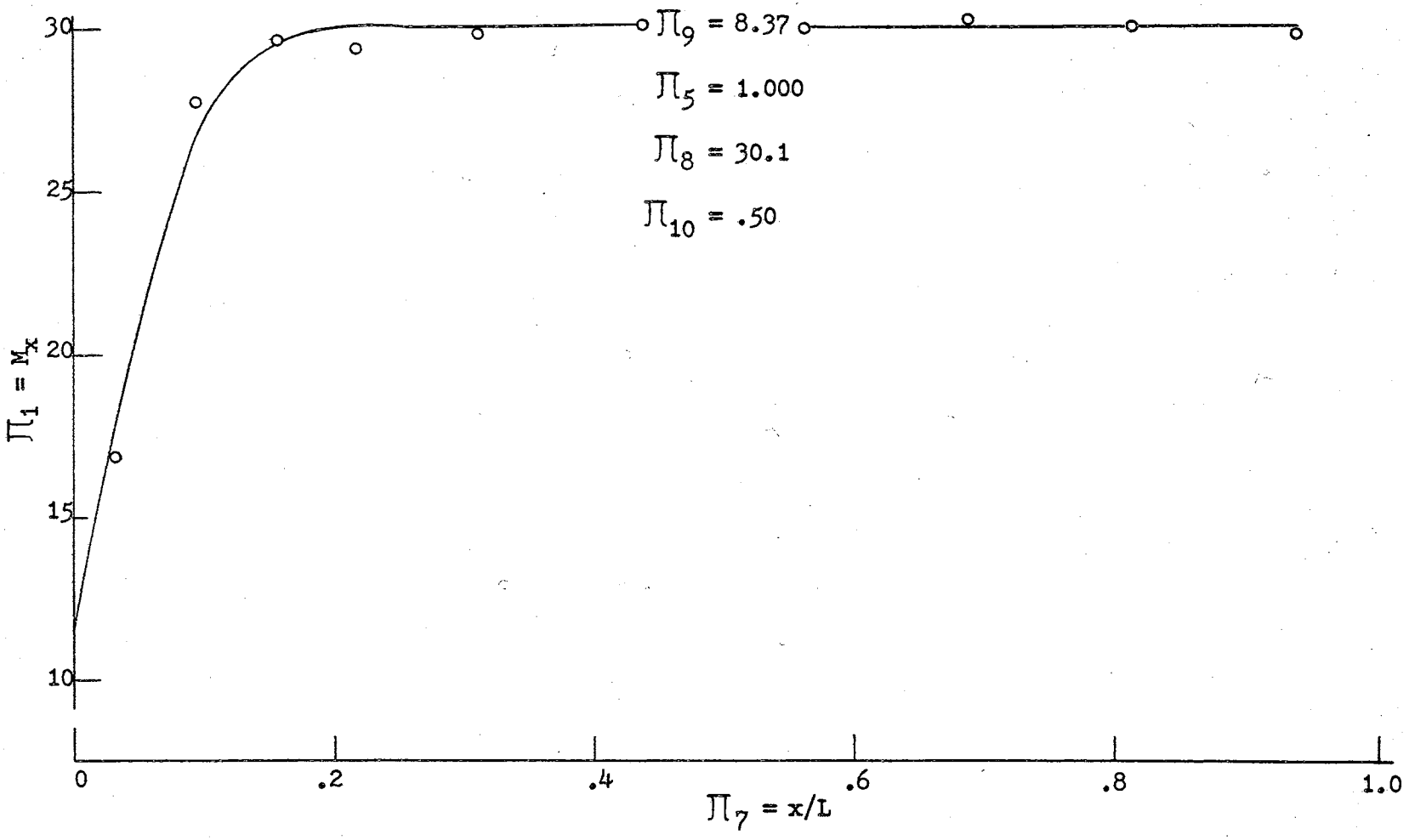

Fig. 38. Π_1 versus Π_7

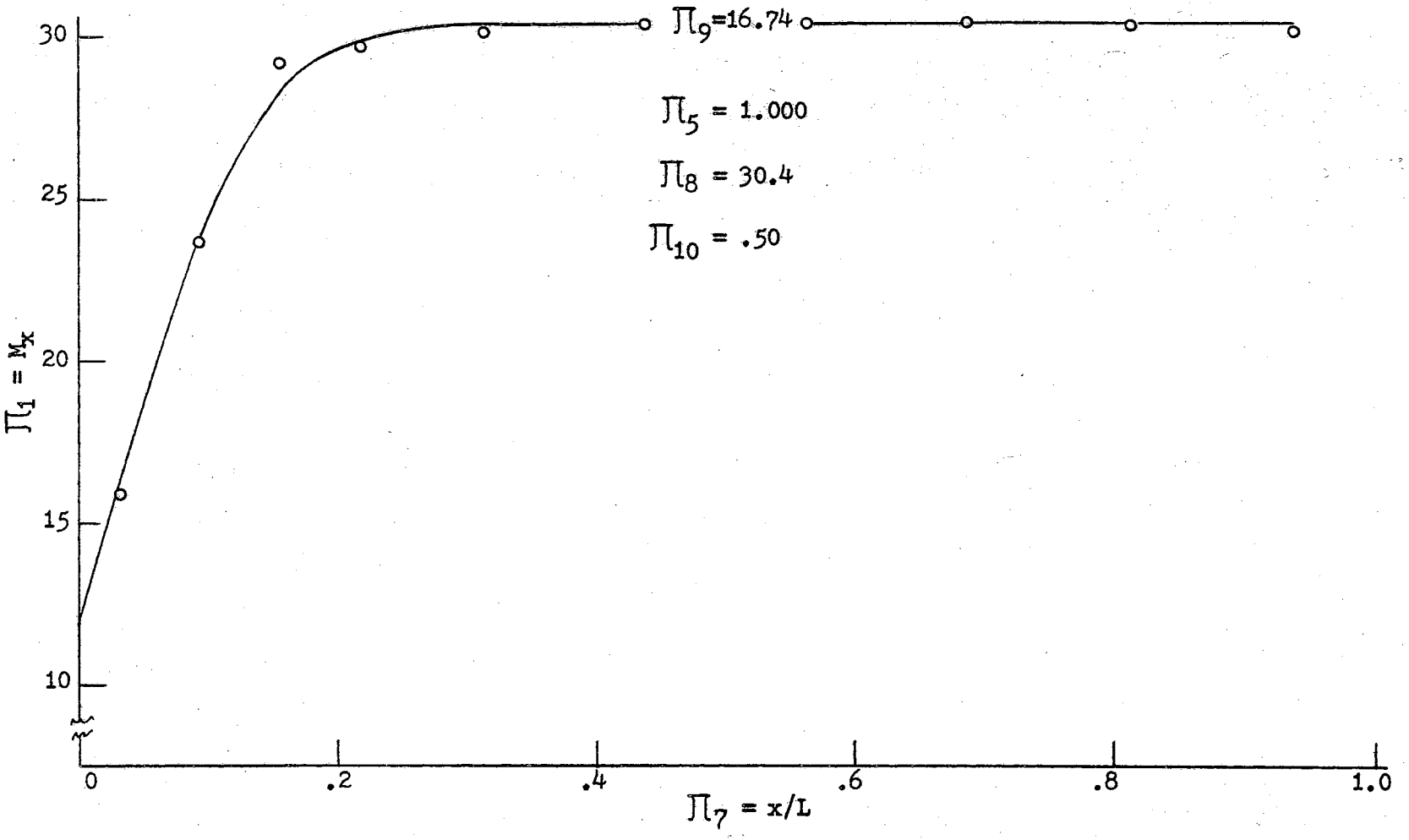

Fig. 39. Π_1 versus Π_7

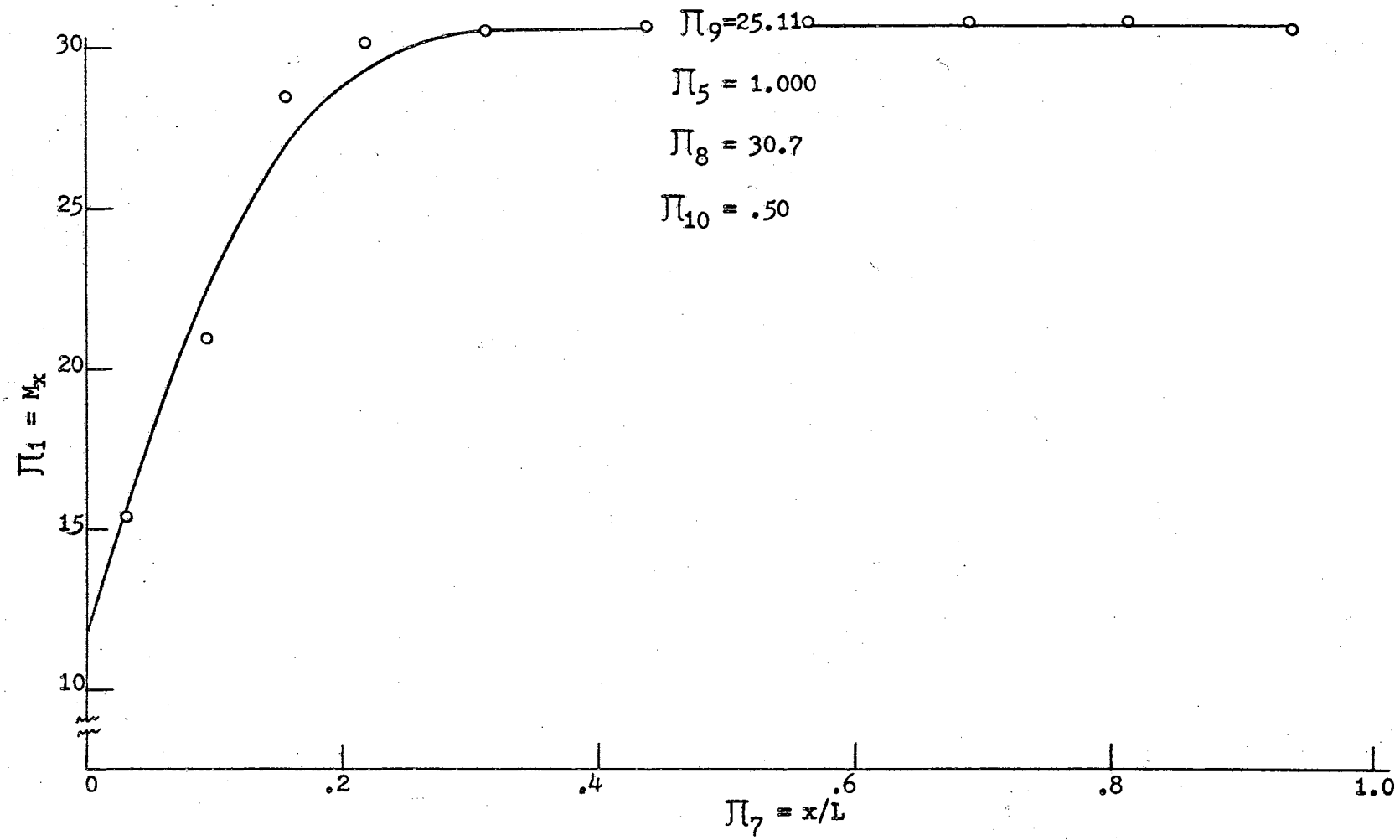

Fig. 40. Π_1 versus Π_7

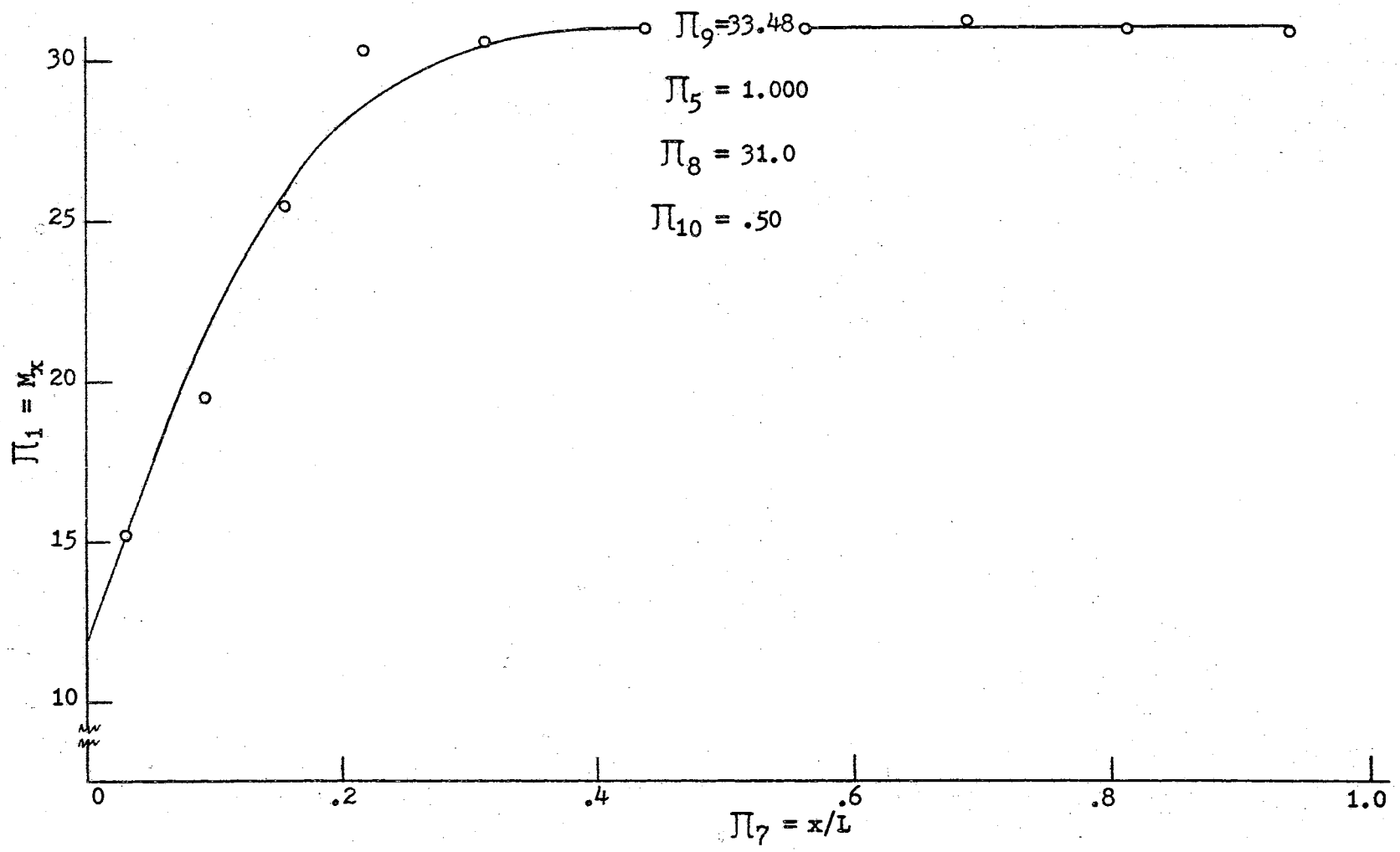

Fig. 41. Π_1 versus Π_7

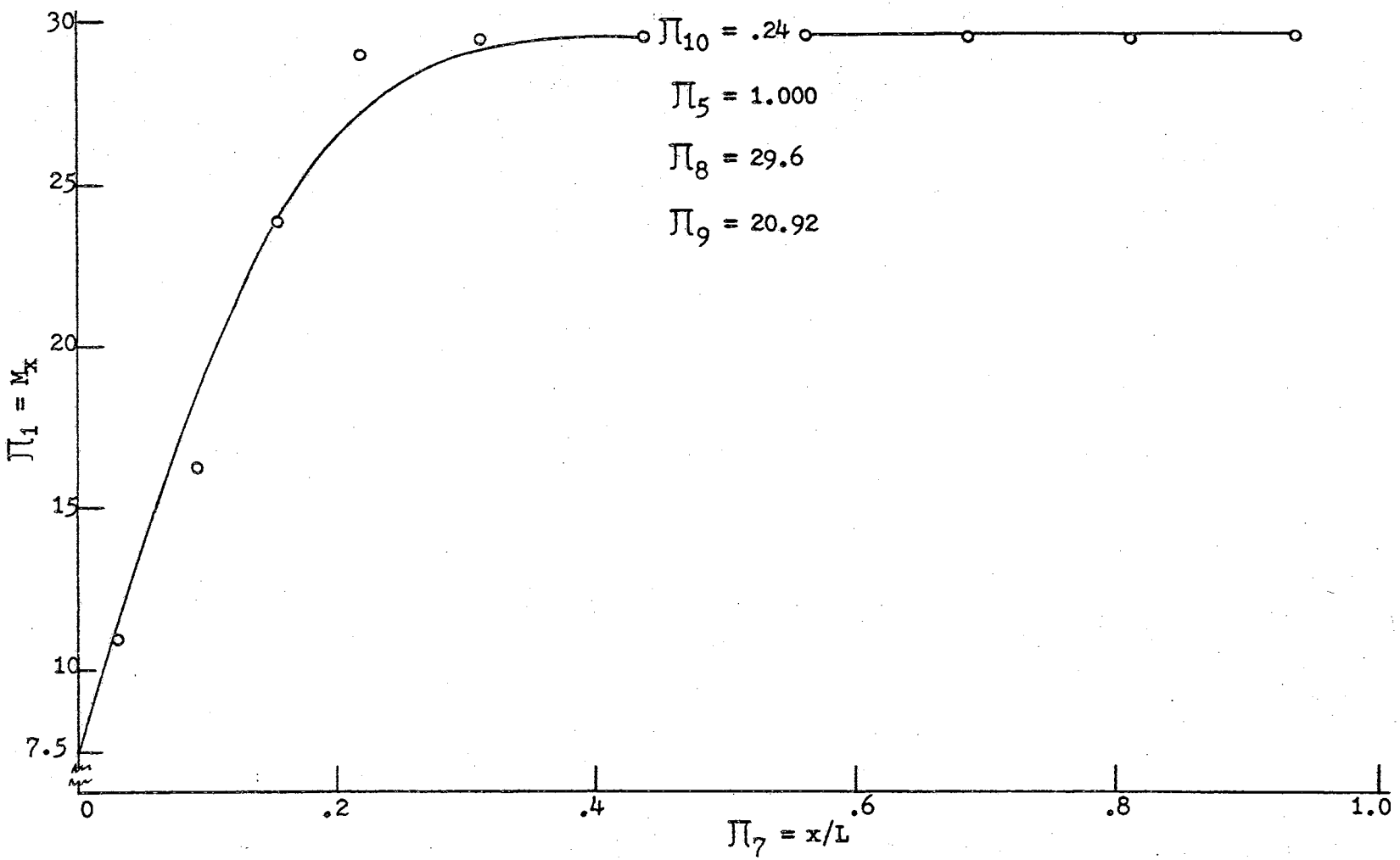

Fig. 42. Π_1 versus Π_7

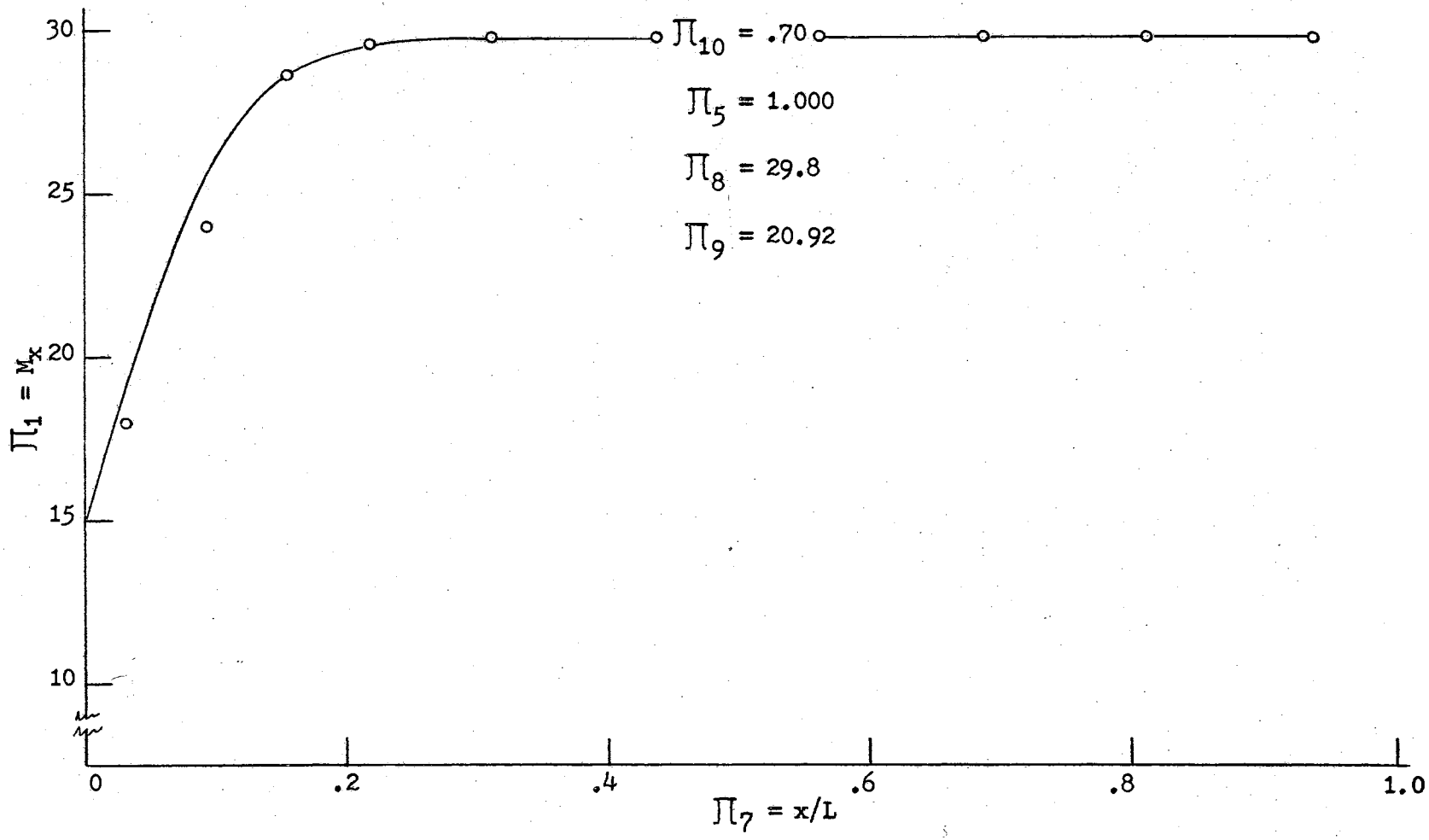

Fig. 43. Π_1 versus Π_7

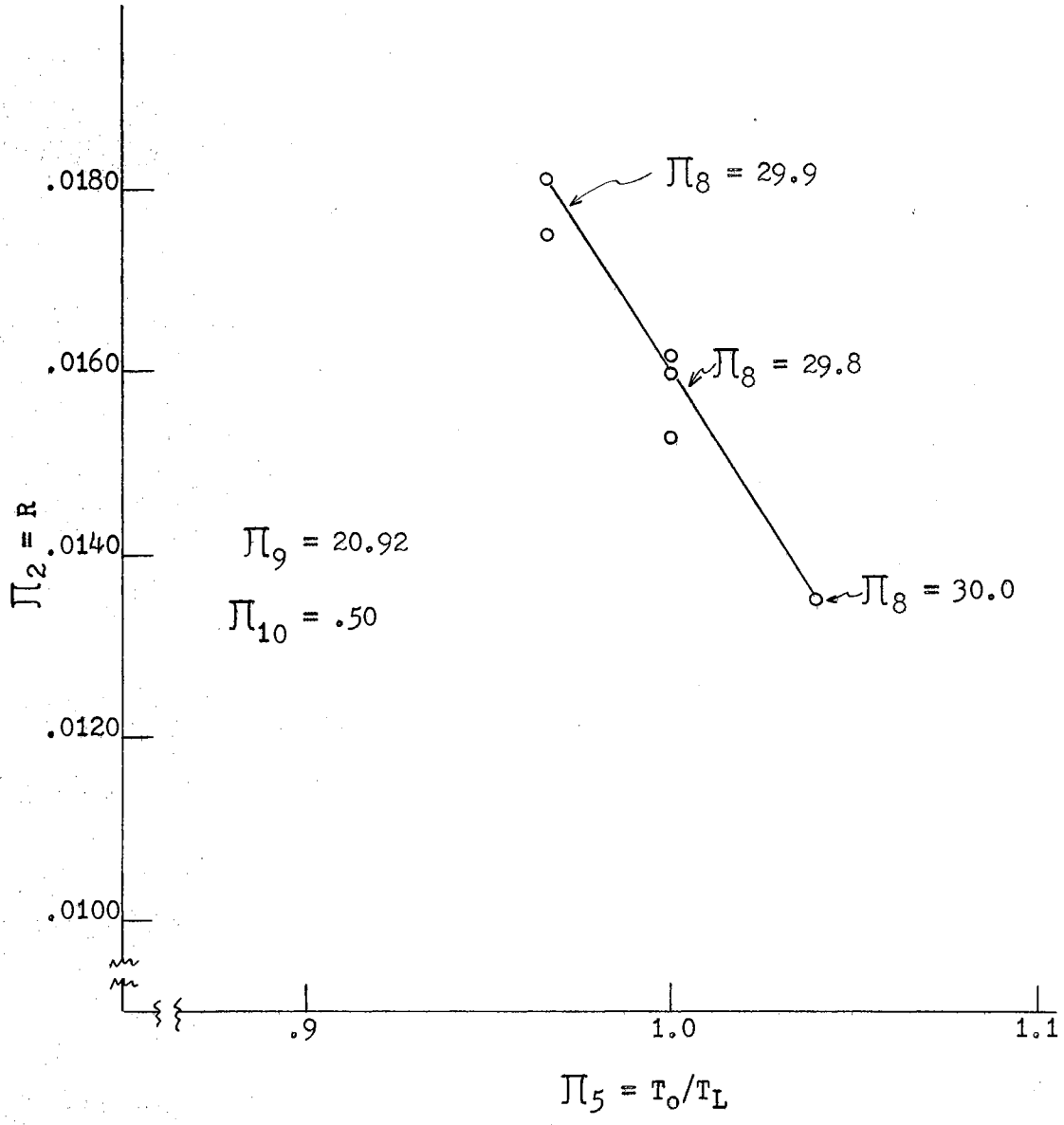

Fig. 44. Π_2 versus Π_5

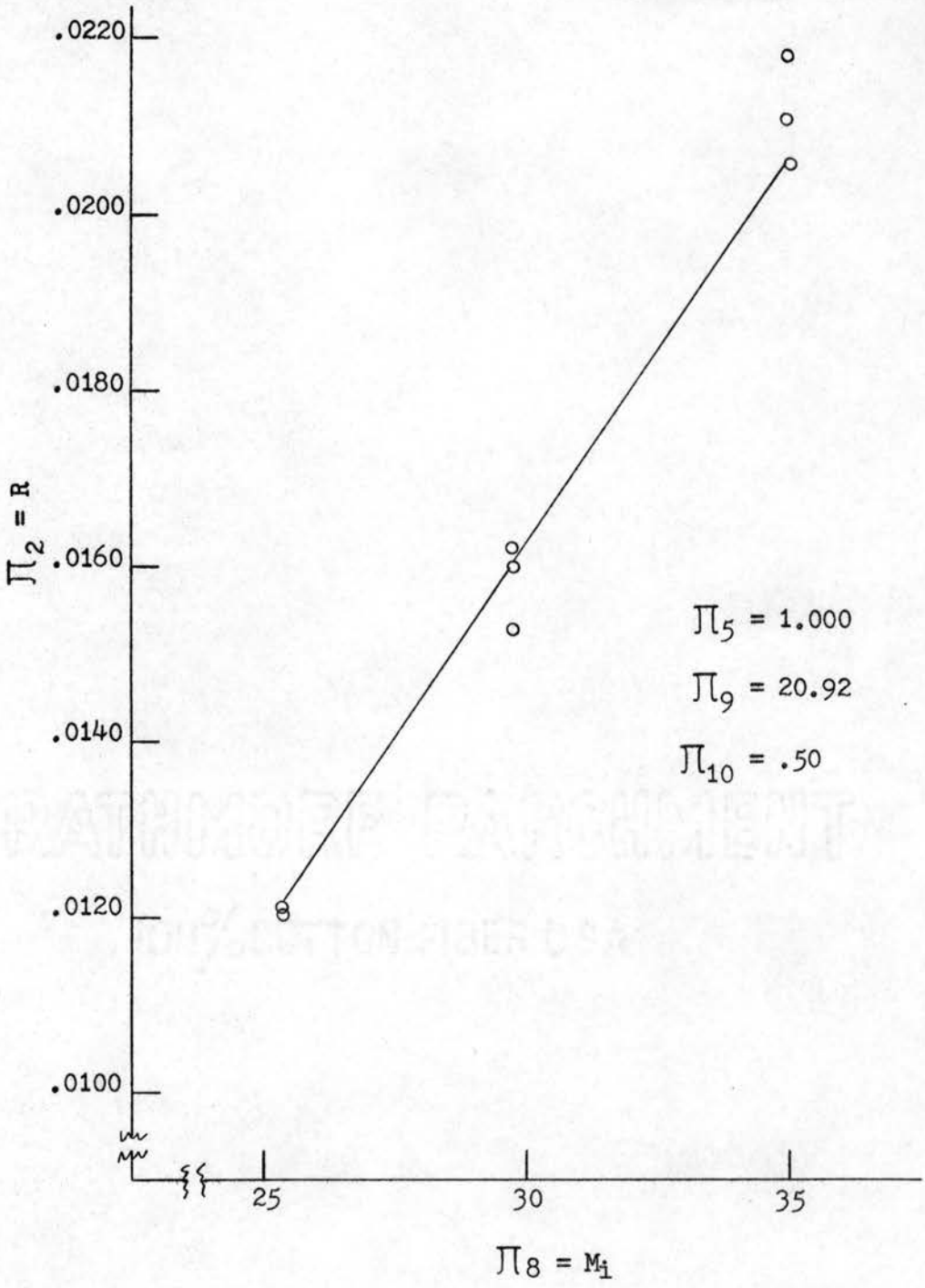

Fig. 45. Π_2 versus Π_8

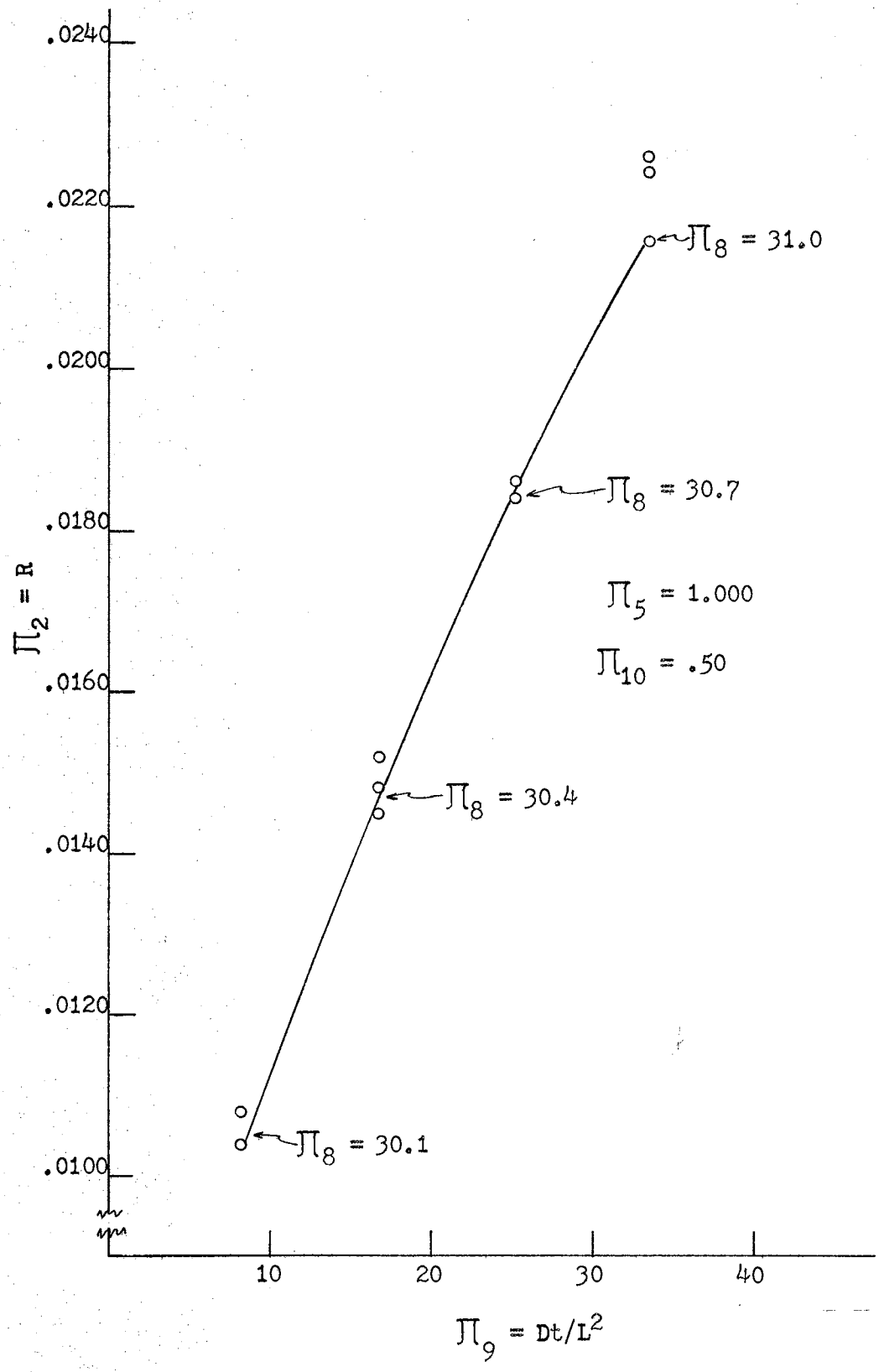

Fig. 46. Π_2 versus Π_9

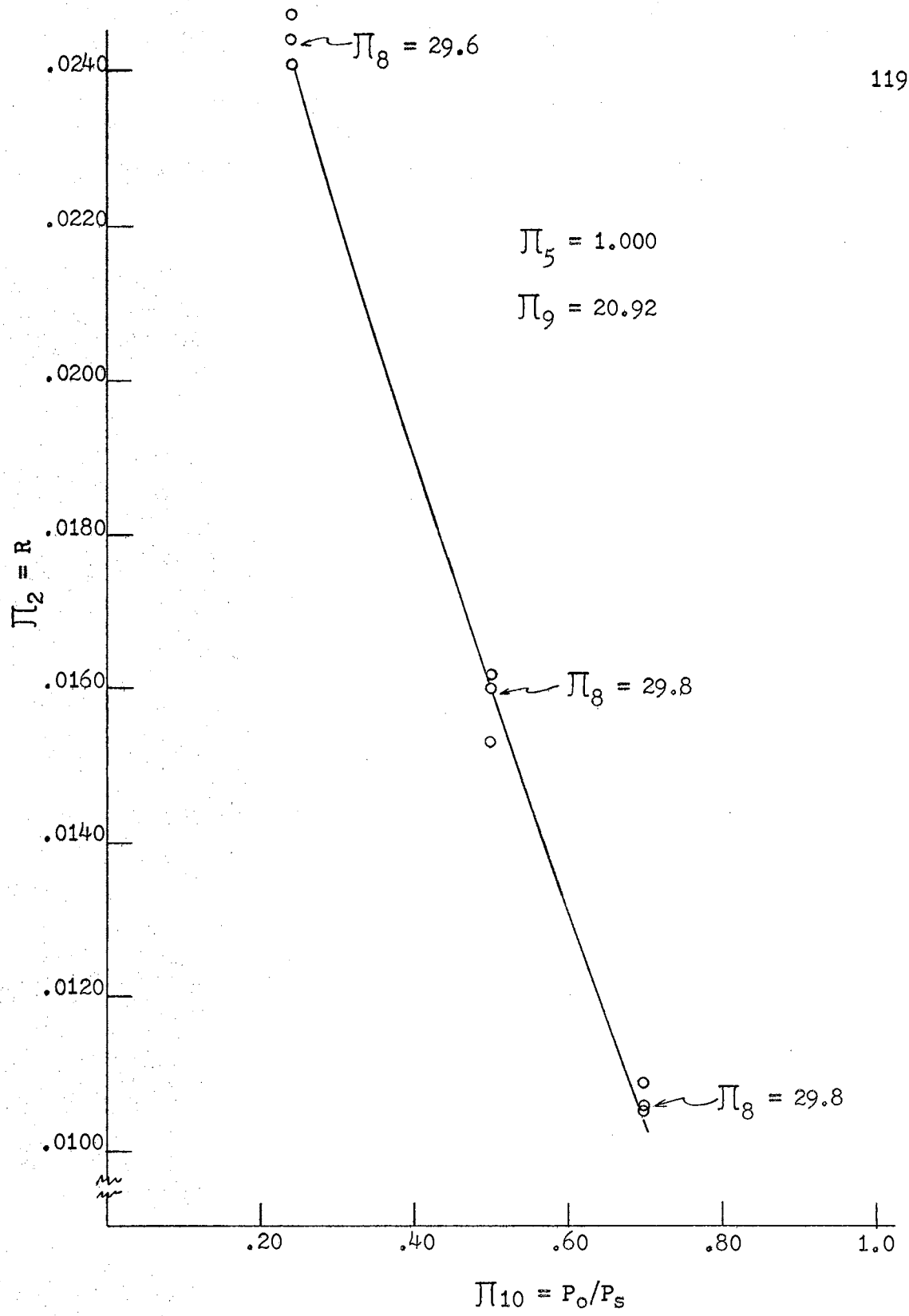

Fig. 47. Π_2 versus Π_{10}

TABLE X

SUMMARY OF b AND r^2 FOR COMPARISON OF PREDICTED AND EXPERIMENTAL VALUES OF Π_1

Π_5	Π_8	Π_9	Π_{10}	b	r^2
.966	29.9	20.92	.50	.93	.95
1.000	29.8	20.92	.50	1.05	.98
1.040	30.0	20.92	.50	.98	1.00
1.000	25.4	20.92	.50	1.07	1.00
1.000	35.0	20.92	.50	1.13	.98
1.000	30.1	8.37	.50	1.07	.98
1.000	30.4	16.74	.50	1.02	.99
1.000	30.7	25.11	.50	1.05	.98
1.000	31.0	33.48	.50	1.05	.98
1.000	29.6	20.92	.24	1.08	.98
1.000	29.8	20.92	.70	1.15	.99

TABLE XI

SUMMARY OF b AND r^2 FOR COMPARISON OF PREDICTED AND EXPERIMENTAL VALUES OF Π_2

Test No.	b	r^2
1	1.07	1.00
2	1.01	1.00
4	.98	1.00
5	1.00	1.00

at 30.0 and .50, respectively.

For any given elapsed drying time, Π_2 was greater with $\Pi_5 = .966$. After 48 hours of elapsed drying time with $\Pi_5 = .966$, Π_2 was .0230. Π_2 was the same value after 60 hours of elapsed drying time with $\Pi_5 = 1.000$. The moisture distributions, Π_1 vs. Π_7, were also identical for the two sets of conditions. The theoretical predictions in Chapter III indicated similar results. That is, as the temperature of the solid decreases in the direction of moisture movement, the drying process is affected as follows: the drying rate is increased relative to the case of no temperature gradient, yet the moisture distributions are similar for given amounts of water removed from the solid. Thus, for a given drying rate, a temperature gradient in the direction of the moisture gradient favors a reduction in the moisture gradient.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

The objectives of this study were to: 1. Determine the effects of a temperature gradient on moisture transfer in porous, hygroscopic solids; 2. Determine the temperature gradients that would exist in a peanut kernel during curing using dielectric and conventional heating; 3. Determine the significance of the temperature gradient in controlling the moisture gradient during the curing process in a model representing the peanut kernel.

A theory of moisture movement in a one-dimensional, porous, hygroscopic solid was presented. The moisture content of the solid was assumed to increase linearly with increasing water vapor concentration and to decrease linearly with increasing absolute temperature. Theoretical predictions for the drying of a one-dimensional peanut kernel indicated that the drying rate was greater with dielectric heating or uniform heat generation than with no heat generation. Related distributions of moisture, water vapor concentration, and temperature were presented. When compared with the conventional drying method (no heat generation), dielectric heating did not alter the distribution of moisture for a given amount of water lost from

the kernel. However, dielectric heating reduced the time required for the kernel to reach a given moisture distribution because of the increased drying rate.

A moisture transfer study was made on insulated, one-dimensional samples with corn meal as the test material. One end of the samples was sealed and the other end of the samples was left open for drying. Basic parameters believed to be important in the study were listed in TABLE I. These parameters were formed into dimensionless ratios or Pi terms, which were treated as variables.

In the experiment, the two dependent variables were (1) $\prod_1$, moisture content (% dry basis) of corn meal at position x along the sample and (2) $\prod_2$, mass of water lost by the sample per unit mass of dry corn meal. The independent variables were (1) $\prod_5$, ratio of absolute temperatures at either end of sample, (2) $\prod_7$, ratio relating the total length of the sample to the length, x, at which $\prod_1$ was measured, (3) $\prod_8$, initial moisture content (% dry basis) of the corn meal, (4) $\prod_9$, product of elapsed drying time and diffusion coefficient of water vapor in corn meal divided by the square of the sample length, and (5) $\prod_{10}$, relative humidity of the drying air.

Prediction equations were developed for $\prod_1$ and $\prod_2$. The equations accounted for at least 95% of the variation of the experimental data. The effect of a temperature gradient on the moisture gradient in the corn meal during drying was similar to that predicted

by the theory. That is, a temperature gradient in the same direction as the moisture gradient produces a greater vapor concentration gradient, relative to the case of no temperature gradient. This greater vapor concentration gradient increases the drying rate. However, for any given amount of water lost, the moisture gradients are comparable. This infers that a temperature gradient can be used to increase the drying rate in a porous, hygroscopic solid without increasing shrinkage stresses due to the moisture gradient.

Conclusions

The following conclusions seem to be justified for the drying of porous, hygroscopic solids. Conclusions 1 and 3 are based on experimental results of the study. The other conclusions are based on both (1) the theory of moisture movement in porous, hygroscopic solids by the mechanism of vapor transfer and (2) the experimental results of the study.

1. The diffusion coefficient of water vapor in the air spaces of a porous, hygroscopic solid increases with increasing temperature and increasing vapor pressure gradients.
2. After a given amount of water has been removed, the moisture gradients are similar whether or not a temperature gradient exists in the same direction of the moisture gradient.
3. Relative to the case of a temperature gradient in the opposite direction of the moisture gradient, the drying

rate is greater when no temperature gradient exists.

4. Relative to the case of no temperature gradient, the drying rate is greater when a temperature gradient exists in the same direction of the moisture gradient. The greater drying rate is a result of a greater vapor concentration or vapor pressure gradient.
5. A temperature gradient in the same direction as the moisture gradient can be used to decrease the drying time, without increasing the shrinkage stresses in the solid due to the moisture gradient.

Suggestions for Future Investigations

The following studies are suggested to obtain information concerning the phenomenon of drying hygroscopic solids common to the agricultural industry:

1. Determine their ultimate strengths.
2. Determine their contraction and expansion characteristics as a function of temperature and moisture content.
3. Determine their thermal properties.
4. Compare their drying rates with and without internal heat generation induced by high-frequency electric fields.
5. Determine their mechanisms of moisture transfer.

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APPENDIX A

GENERAL SOLUTION OF VAPOR AND HEAT DIFFUSION EQUATIONS IN TERMS OF DIMENSIONLESS QUANTITIES

Let $C' = \frac{C - C_b}{C_o - C_b} = \frac{\Delta C}{\Delta C_o}$, $T' = \frac{T - T_b}{T_o - T_b} = \frac{\Delta T}{\Delta T_o}$

where T_b, C_b = Respectively, temperature and water vapor concentration at boundary ($x' = 0$, $x' = 2$)

T_o, C_o = Respectively, initial conditions of temperature and water vapor concentration within solid ($0 \leq x' \leq 2$)

These conditions are shown in Fig. 13. Then equation (3 - 2a) can be written

$$D_s \frac{\partial^2 C'}{\partial x^2} = f \frac{\partial C'}{\partial t} + \frac{(1-f)}{\Delta C_o} d_s \frac{\partial M}{\partial t} \qquad (3 - 2')$$

Equation (3 - 3a) becomes

$$c_s d \frac{\partial T'}{\partial t} = K \frac{\partial^2 T'}{\partial x^2} + \frac{(hd)}{\Delta T_o} \frac{\partial M}{\partial t} \qquad (3 - 3')$$

Using $\frac{\partial M}{\partial T} = -b$ and $\frac{\partial M}{\partial C} = a$

Equation (3 - 2') becomes

$$D_s \frac{\partial^2 C'}{\partial x^2} - f \frac{\partial C'}{\partial t} - \frac{(1-f)\, d_s}{\Delta C_o} \left[-b \frac{\partial(\Delta T)}{\partial t} + a \frac{\partial(\Delta C)}{\partial t} \right] = 0 \quad (3 - 2a')$$

Equation (3 - 3') becomes

$$c_s d \frac{\partial T'}{\partial t} - K \frac{\partial^2 T'}{\partial x^2} - \frac{hd}{\Delta T_o} \left[-b \frac{\partial(\Delta T)}{\partial t} + a \frac{\partial(\Delta C)}{\partial t} \right] = 0 \quad (3 - 3a')$$

Equation (3 - 2a') becomes

$$D_s \frac{\partial^2 C'}{\partial x^2} - f \frac{\partial C'}{\partial t} - \frac{(1-f)}{\Delta C_o} d_s \left[-b(\Delta T_o) \frac{\partial T'}{\partial t} + a(\Delta C_o) \frac{\partial C'}{\partial t} \right] = 0 \qquad (3 - 2b')$$

Equation (3 - 3a') becomes

$$c_s d \frac{\partial T'}{\partial t} - K \frac{\partial^2 T'}{\partial x^2} - \frac{hd}{\Delta T_o} \left[-b(\Delta T_o) \frac{\partial T'}{\partial t} + a(\Delta C_o) \frac{\partial C'}{\partial t} \right] = 0 \qquad (3 - 3b')$$

Equation (3 - 2b') becomes

$$D \frac{\partial^2 C'}{\partial x^2} - \frac{\partial}{\partial t} \left[C' - G'T' \right] = 0 \qquad (3 - 2c')$$

where $D = \dfrac{D_s}{d_s a (1-f) + f}$

$$G' = G \left(\Delta T_o / \Delta C_o \right)$$

$$G = \frac{(1-f) d_s b}{d_s a (1-f) + f}$$

Equation (3 - 3b') becomes

$$H \frac{\partial^2 T'}{\partial x^2} - \frac{\partial}{\partial t} \left[T' - I'C' \right] = 0 \qquad (3 - 3c')$$

where $H = \dfrac{K}{d (c_s + hb)}$

$$I' = I \left(\Delta C_o / \Delta T_o \right)$$

$$I = \frac{ah}{hb + c_s}$$

Let $D' = D/H$

$$x' = x/L$$

$$t' = \frac{Ht}{L^2}$$

Equation (3 - 2c') becomes

$$D' \frac{\partial^2 C'}{\partial (x')^2} - \frac{\partial}{\partial t'} \left[C' - G'T' \right] = 0 \qquad (3 - 2d')$$

Equation (3 - 3c') becomes

$$\frac{\partial^2 T'}{\partial (x')^2} - \frac{\partial}{\partial t'} \left[T' - I'C' \right] = 0 \qquad (3 - 3d')$$

Multiplying equation (3 - 2d') by R'/D' and equation (3 - 3d') by S' and adding yields

$$\frac{\partial}{\partial (x')^2} \left[R'C' + S'T' \right] - \frac{\partial}{\partial t'} \left[\left(\frac{R'}{D'} - S'I' \right) C' + \left(S' - \frac{G'R'}{D'} \right) T' \right] = 0 \qquad (3 - 4')$$

For equation (3 - 4') to take the form of a diffusion equation

$$\frac{R'}{D'} - S'I' = R'U'^2 \quad , \quad S' - \frac{G'R'}{D'} = S'U'^2$$

Then

$$\frac{1}{D'} - \frac{S'I'}{R'} = 1 - \frac{G'R'}{S'D'} = U'^2 \quad , \quad \frac{R'}{S'} = (1-U'^2)\frac{D'}{G'}$$

$$\frac{R'}{S'D'} - I' = U'^2 \frac{R'}{S'} \quad , \quad \frac{R'}{S'} = \frac{I'D'}{1 - U'^2D'}$$

$$\frac{R'}{S'} = (1-U'^2)\frac{D'}{G'} \quad , \quad \frac{I'}{1 - U'^2D'} = \frac{(1 - U'^2)}{G'}$$

It follows that

$$(1 - U'^2)(1 - U'^2D') = I'G'$$

$$(1 - I'G') - (D' + 1)U'^2 + D'U'^4 = 0$$

Solving the quadratic for U'^2

$$U'^2_1 = \frac{D' + 1 + \left[(D'-1)^2 + 4D'I'G'\right]^{\frac{1}{2}}}{2D'}$$

$$U'^2_2 = \frac{D' + 1 - \left[(D'-1)^2 + 4D'I'G'\right]^{\frac{1}{2}}}{2D'}$$

Then

$$\frac{S'_1}{R'_1} = (\frac{1}{D'} - U'^2_1)\frac{1}{I'} \quad , \quad \frac{R'_2}{S'_2} = (1 - U'^2_2)\frac{D'}{G'}$$

If R'_1 and S'_2 equal unity

$$S'_1 = \left(\frac{1}{D'} - U'^2_1\right)\frac{1}{I'} \quad , \quad R'_2 = (1 - U'^2_2)\frac{D'}{G'}$$

Equation (3 - 4') can be written

$$\frac{1}{U'^2}\frac{\partial^2}{\partial(x')^2}\left[R'C' + S'T'\right] - \frac{\partial}{\partial t'}\left[R'C' + S'T'\right] = 0$$

APPENDIX B

GENERAL SOLUTION OF VAPOR AND HEAT DIFFUSION EQUATIONS IN TERMS OF DIMENSIONLESS QUANTITIES WITH UNIFORM HEAT GENERATION

With uniform heat generation, a heat balance on a differential element of the solid in Fig. 12 yields

$$c_s d \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} + hd \frac{\partial M}{\partial t} + q$$

where q = heat generation, $\frac{\text{Btu}}{\text{hr. ft.}^3}$

which becomes on the introduction of T' as defined in Appendix A

$$c_s d \frac{\partial T'}{\partial t} = K \frac{\partial^2 T'}{\partial x^2} + \frac{hd}{\Delta T_o} \frac{\partial M}{\partial t} + \frac{q}{\Delta T_o} \qquad (3 - 5')$$

The derivation follows that presented above in Appendix A for the case of no heat generation. There is, of course, the addition of the heat generation term in the heat diffusion equation. Equation (3 - 5') reduces to

$$\frac{\partial^2 T'}{\partial (x')^2} - \frac{\partial}{\partial t'} \left[T' - I'C' \right] + \frac{Q'D'I'}{F'} = 0 \qquad (3 - 6')$$

where $Q' = \frac{qL^2}{dhD}$

$F' = (a)\ (\Delta C_o)$

The vapor diffusion equation is unchanged.

$$D' \frac{\partial^2 C'}{\partial (x')^2} - \frac{\partial}{\partial t'}\left[C' - G'T'\right] = 0 \qquad (3 - 7')$$

Combining equations (3 - 6') and (3 - 7') yields the general partial differential equation

$$\frac{\partial^2}{\partial (x')^2}\left[R'C' + S'T'\right] + \frac{S'Q'D'I'}{F'} - \frac{\partial}{\partial t'}\left[\left(\frac{R'}{D'} - I'S'\right)C' + \left(S' - \frac{G'R'}{D'}\right)T'\right] = 0$$

or

$$\frac{1}{U'^2}\frac{\partial^2}{\partial (x')^2}\left[RC' + ST'\right] + \frac{S'Q'D'I'}{U'^2F'} - \frac{\partial}{\partial t'}\left[R'C' + S'T'\right] = 0 \qquad (3 - 8')$$

Let

$$R'C' + S'T' = P' + X' \qquad (3 - 9')$$

where P' = function of x' and t'

X' = function of x' only

Substitution of equation (3 - 9') into equation (3 - 8') gives

$$\frac{\partial^2 P'}{\partial (x')^2} + \frac{d^2 X'}{d\,(x')^2} - kU'^2 - U'^2\left(\frac{\partial P'}{\partial t'}\right) = 0 \qquad (3 - 10')$$

where $k = \frac{-S'Q'D'I'}{U'^2F'}$

To reduce equation (3 - 10') to a separable partial differential equation

$$\frac{d^2X'}{d\,(x')^2} - kU'^2 = 0 \qquad (3 - 11')$$

The boundary conditions for T' and C' in Fig. 13 are used to derive the boundary conditions for X'. They are

1. $X' = 0,\ x' = 0$
2. $X' = 0,\ x' = 2$

The solution to equation (3 - 11') is

$$X' = \frac{-kU'^2}{2}\left[2x' - (x')^2\right]$$

Then from equation (3 - 9')

$$P' = R'C' + S'T' + \frac{kU'^2}{2}\left[2x' - (x')^2\right]$$

The boundary conditions for P' are

1. $P' = 0,\ x' = 0$
2. $P' = 0,\ x' = 2$

The initial conditions for P' are

$$P' = R' + S' + \frac{kU'^2}{2}\left[2x' - (x')^2\right] \quad , \ t' = 0,\ 0 \leq x' \leq 2$$

The solution to the equation

$$\frac{\partial^2 P'}{\partial (x')^2} - U'^2\left[\frac{\partial P'}{\partial t'}\right] = 0 \qquad (3 - 10a')$$

takes the form

$$P' = \sum_{n=1}^{\infty} P_n \sin \frac{n\pi x'}{2} \left[\exp\left(-n^2\pi^2 t'/4U'^2\right)\right] \qquad (3 - 12')$$

Substitution of the initial conditions of P' in equation (3 - 12') yields

$$R' + S' + \frac{kU'^2}{2}\left[2x' - (x')^2\right] = \sum_{n=1}^{\infty} P_n \sin \frac{n\pi x'}{2} \qquad (3 - 13')$$

Multiplying equation (3 - 13') by $\sin \frac{m\pi x'}{2}$ and integrating between $x' = 0$ and $x' = 2$ gives

$$P_n = \frac{4}{n\pi}\left[R' + S' + \frac{4kU'^2}{(n\pi)^2}\right] \quad , n = 1, 3, 5, 7 \text{ ---}$$

The two solutions to equation (3 - 9') become

$$C' + S_1'T' = N_1 + \frac{4}{\pi}\sum_{n=1}^{\infty} W_1\, YZ_1 = V_5 \qquad (3 - 14')$$

$$R_2'C' + T' = N_2 + \frac{4}{\pi}\sum_{n=1}^{\infty} W_2\, YZ_2 = V_6 \qquad (3 - 15')$$

where $N_1 = \frac{J_1'}{2}\left[2x' - (x')^2\right]$, $J_1' = \frac{S_1'Q'D'I'}{F'}$

$$N_2 = \frac{J_2'}{2}\left[2x' - (x')^2\right] \quad , J_2' = \frac{Q'D'I'}{F'}$$

$$W_1 = 1 + S_1' - \frac{4J_1'}{(2n-1)^2\pi^2}$$

$$W_2 = R_2' + 1 - \frac{4J_2'}{(2n-1)^2\pi^2}$$

Solving equations (3 - 14') and (3 - 15') for C' and T' yields

$$C' = \frac{V_5 - S_1'V_6}{1 - S_1'R_2'} \qquad (3 - 16')$$

$$T' = \frac{V_6 - R_2'V_5}{1 - S_1'R_2'} \qquad (3 - 17')$$

APPENDIX C

RAW DATA AND SAMPLE CALCULATIONS FOR DIFFUSION COEFFICIENTS

APPENDIX C

Letters A and B corresponded to the flasks suspended in the jars with potassium acetate and potassium carbonate, respectively. For each jar, subscripts 1, 2, and 3 referred to the two modified flasks with corn meal and the intact flask with stagnant air, respectively. TABLE XII shows the physical dimensions of the flask necks.

TABLE XII

PHYSICAL DIMENSIONS OF FLASK NECKS

Flask	Length, ft.	Diameter, ft.
A_1	0.1354	0.0500
A_2	0.1354	0.0503
A_3	0.1667	0.0472
B_1	0.1224	0.0505
B_2	0.1198	0.0505
B_3	0.1667	0.0472

The flask weight losses, time required for the weight losses, and calculated diffusion coefficients are presented in TABLES XIII and XIV for 530 and 541°R., respectively.

APPENDIX C

TABLE XIII

FLASK WEIGHT LOSSES WITH CORRESPONDING TIME REQUIRED AND DIFFUSION COEFFICIENTS AT 530°R.

Flask	Weight Loss, Grams	Time Required for Weight Loss, Hours	Diffusion Coefficient, $ft.^2/hr.$
A_1	0.0333	23.83	0.28
	0.0329	23.17	0.29
	0.0364	23.75	0.31
	0.0358	24.08	0.30
	0.0307	23.92	0.26
A_2	0.0344	23.83	0.29
	0.0381	23.75	0.32
	0.0355	24.08	0.29
	0.0325	23.92	0.27
A_3	0.0781	23.83	0.91
	0.0830	23.17	1.00
	0.0841	23.75	0.98
	0.0796	24.08	0.92
B_1	0.0258	25.00	0.28
	0.0211	23.83	0.24
	0.0197	23.00	0.23
	0.0288	23.92	0.32
	0.0233	24.17	0.26
B_2	0.0245	25.00	0.26
B_3	0.0607	25.00	1.02
	0.0513	23.83	0.91
	0.0550	23.00	1.01
	0.0581	23.92	1.02
	0.0550	24.17	0.96

APPENDIX C

TABLE XIV

FLASK WEIGHT LOSSES WITH CORRESPONDING TIME REQUIRED AND DIFFUSION COEFFICIENTS AT 541°R.

Flask	Weight Loss, Grams	Time Required for Weight Loss, Hours	Diffusion Coefficient, $ft.^2/hr.$
A_1	0.0527	24.00	0.31
	0.0549	24.25	0.32
	0.0561	24.17	0.33
	0.0552	24.00	0.33
	0.0521	23.75	0.31
A_2	0.0542	24.00	0.32
	0.0573	24.25	0.33
	0.0561	24.27	0.33
	0.0559	24.00	0.33
	0.0528	23.75	0.32
A_3	0.1200	24.00	0.99
	0.1293	24.25	1.06
	0.1260	24.17	1.03
	0.1233	24.00	1.02
	0.1184	23.75	0.99
B_1	0.0379	24.00	0.30
	0.0402	24.25	0.31
	0.0391	23.83	0.31
	0.0348	23.83	0.28
B_2	0.0363	24.00	0.28
	0.0381	24.25	0.29
	0.0376	23.83	0.29
	0.0364	24.33	0.28
	0.0345	23.83	0.27
B_3	0.0830	24.00	1.02
	0.0882	24.25	1.00
	0.0852	23.83	1.05
	0.0843	24.33	1.04
	0.0817	23.83	1.01

APPENDIX C

Inside the jars, the potassium acetate and potassium carbonate solutions were assumed to maintain relative humidities of 22.7 and 43.8%, respectively. The relative humidity over the potassium chromate solution in the flask bulbs was assumed as 86.5%.

Sample calculations are presented for the first diffusion coefficient in TABLE XIII. From equation (4 - 7)

$$D = N_V LRT/P \ln (P-P_{vL})/(P-P_{vo})$$

$L = 0.1354$ ft. $\qquad T = 530^{\circ}R$

$R = 0.73$ atm. ft.^{3}/lb. mole $^{\circ}R$ $\qquad P = 1.0$ atm.

Cross-sectional area of flask neck is

$$(.785)\ (.05)^2 = 0.00196 \text{ ft.}^2$$

$$N_V = (0.0333)/(18)\ (453.6)\ (23.83)\ (.00196)$$

$$N_V = 0.0000868 \text{ lb. moles/hr. ft.}^2$$

Standard atmospheric pressure = 29.921 in. Hg.

Vapor pressure of water at $530^{\circ}R$ = 0.73915 in. Hg.

Therefore

$$P_{vo} = \frac{.73915\ (.865)}{29.921} = 0.021368 \text{ atm.}$$

$$P_{vL} = \frac{.73915\ (.227)}{29.921} = 0.005608 \text{ atm.}$$

$$\ln (P-P_{vL})/(P-P_{vo}) = 0.0162$$

$$D = (.0000868)(.1354)(.73)(530)/.0162 = 0.28 \text{ ft.}^2/\text{hr.}$$

APPENDIX D

RAW DATA FOR INITIAL SAMPLES

The four headings under INITIAL SAMPLES on each page of Appendix D represent:

MI = M_i = initial moisture content, % dry basis

HOURS ELAPSED = elapsed drying time in hours for initial samples = 0

TEST NO = number of test in experimental schedule

PI TERM NO = number of Pi term varied in test

PI TERM LEVEL = level(s) of Pi term varied in test for which INITIAL SAMPLES represent

INITIAL SAMPLES

MI	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
25.4	0	1	8	25.400

WEIGHT IN GRAMS

X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
.0625	10.0141	9.8750	9.3145
.1875	9.9591	9.8535	9.4180
.3125	9.9353	9.7916	9.2301
.4375	9.8174	9.6865	9.1659
.5625	9.7472	9.6168	9.1024
.6875	10.1975	10.0016	9.2366
.8125	10.4252	10.2665	9.6441
.9375	10.2068	10.0562	9.4607
.0625	10.3959	10.1859	9.3687
.1875	10.5792	10.3864	9.6309
.3125	10.1185	9.9279	9.1836
.4375	10.5879	10.3652	9.4954
.5625	10.4420	10.2492	9.4916
.6875	10.5328	10.3032	9.4135
.8125	10.2364	10.0547	9.3485
.9375	10.1703	10.0066	9.3646
.0625	9.7988	9.6300	8.9624
.1875	9.8484	9.6597	8.9225
.3125	9.8082	9.6358	8.9621
.4375	10.0004	9.7934	8.9810
.5625	9.6070	9.4503	8.8345
.6875	9.9516	9.7545	8.9872
.8125	9.4665	9.3123	8.7102
.9375	9.3544	9.2434	8.8038

INITIAL SAMPLES

MI	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
29.8	0	1	8	29.800

WEIGHT IN GRAMS

X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
.0625	9.6275	9.4417	8.8158
.1875	9.8197	9.5999	8.8665
.3125	9.3495	9.1829	8.6250
.4375	9.0884	8.8718	8.1469
.5625	9.2044	9.0315	8.4492
.6875	9.9128	9.6980	8.9835
.8125	9.3378	9.1521	8.5357
.9375	9.3497	9.1859	8.6386
.0625	9.0336	8.8511	8.2357
.1875	9.3595	9.1251	8.3386
.3125	9.1931	9.0034	8.3655
.4375	9.4591	9.2594	8.5849
.5625	9.4418	9.2391	8.5533
.6875	9.0329	8.8302	8.1571
.8125	9.3275	9.1619	8.6085
.9375	9.1987	9.0285	8.4518

INITIAL SAMPLES

MI	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
35.0	0	1	8	35.000

WEIGHT IN GRAMS

X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
.0625	9.9031	9.7141	9.1667
.1875	10.0971	9.8558	9.1717
.3125	9.9482	9.7566	9.2095
.4375	10.2313	10.0321	9.4604
.5625	10.1373	9.9432	9.3927
.6875	10.1568	9.9236	9.2665
.8125	10.1165	9.8623	9.1502
.9375	9.7961	9.6014	9.0464
.0625	9.6308	9.4133	8.7645
.1875	9.6515	9.3968	8.6651
.3125	9.2862	9.0850	8.5040
.4375	9.4887	9.2249	8.4671
.5625	9.4305	9.2158	8.5998
.6875	9.4242	9.1729	8.4548
.8125	9.3136	9.1175	8.5565
.9375	9.3310	9.1027	8.4437

INITIAL SAMPLES

MI	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
30.1	0	2	9	ALL

WEIGHT IN GRAMS

X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
.0625	10.0943	9.8695	9.1263
.1875	10.1997	9.9943	9.3174
.3125	9.8333	9.6606	9.0876
.4375	10.2510	10.0100	9.2151
.5625	10.1855	9.9860	9.3273
.6875	9.6702	9.4530	8.7379
.8125	9.6611	9.4473	8.7454
.9375	9.8479	9.5960	8.7708
.0625	8.9769	8.7861	8.1469
.1875	9.3028	9.0862	8.3660
.3125	9.4215	9.2368	8.6247
.4375	9.7612	9.5430	8.8158
.5625	9.7401	9.5605	8.9621
.6875	9.9594	9.7319	8.9810
.8125	9.7974	9.5804	8.8665
.9375	9.8316	9.6001	8.8345
.0625	9.4765	9.2963	8.6918
.1875	9.8067	9.6002	8.9106
.3125	9.6700	9.4741	8.8195
.4375	9.6715	9.4694	8.7937
.5625	9.4884	9.3153	8.7359
.6875	9.6353	9.4133	8.6764
.8125	9.6488	9.4693	8.8708
.9375	9.6829	9.4638	8.7324

INITIAL SAMPLES

MI	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
29.9	0	4	5	.966

WEIGHT IN GRAMS

X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
.0625	9.3516	9.1756	8.5848
.1875	9.4583	9.2534	8.5651
.3125	9.5347	9.3202	8.6045
.4375	9.6458	9.4067	8.6100
.5625	9.5780	9.3581	8.6239
.6875	9.6761	9.4353	8.6353
.8125	9.5660	9.3525	8.6391
.9375	9.7864	9.5254	8.6490
.0625	9.4417	9.2742	8.7093
.1875	9.6310	9.4201	8.7112
.3125	9.5168	9.3324	8.7150
.4375	9.7573	9.5228	8.7342
.5625	9.6045	9.4045	8.7347
.6875	9.7676	9.5309	8.7382
.8125	9.7461	9.5155	8.7443
.9375	9.7631	9.5308	8.7458
.0625	9.4425	9.2622	8.6584
.1875	9.6818	9.4465	8.6622
.3125	9.3470	9.1898	8.6650
.4375	9.5809	9.3695	8.6659
.5625	9.5558	9.3536	8.6823
.6875	9.5200	9.3298	8.6983
.8125	9.6065	9.3967	8.7014
.9375	9.6631	9.4423	8.7068

INITIAL SAMPLES

MI	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
26.5	0	4	5	1.040

WEIGHT IN GRAMS

X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
.0625	9.4248	9.2259	8.4674
.1875	9.5210	9.3076	8.5040
.3125	9.3794	9.2089	8.5675
.4375	9.7137	9.4933	8.6663
.5625	9.3600	9.2292	8.7351
.6875	9.6315	9.4491	8.7648
.8125	9.8922	9.7012	8.9873
.9375	10.1623	9.9270	9.0470
.0625	10.0317	9.8611	9.2160
.1875	9.9726	9.7961	9.1273
.3125	10.0518	9.8808	9.2375
.4375	10.3650	10.1452	9.3149
.5625	10.0905	9.9287	9.3187
.6875	10.2523	10.0588	9.3296
.8125	10.2690	10.0992	9.4616
.9375	10.6491	10.4381	9.6446
.0625	9.3886	9.2300	8.6252
.1875	9.8362	9.5932	8.6774
.3125	9.5986	9.4091	8.6927
.4375	9.6913	9.4859	8.7107
.5625	9.5073	9.3447	8.7300
.6875	9.7168	9.5106	8.7369
.8125	9.6278	9.4410	8.7405
.9375	9.7343	9.5271	8.7471

INITIAL SAMPLES

MI	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
31.1	0	4	5	1.040

WEIGHT IN GRAMS

X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
.0625	9.4939	9.2896	8.6215
.1875	9.6338	9.4086	8.6819
.3125	9.4777	9.2718	8.6081
.4375	9.5922	9.3777	8.6912
.5625	9.3467	9.1729	8.6145
.6875	9.4631	9.2581	8.6010
.8125	9.5302	9.3196	8.6413
.9375	9.9719	9.7126	8.8793
.0625	9.6470	9.4521	8.8158
.1875	9.8767	9.6260	8.8201
.3125	9.6877	9.4846	8.8349
.4375	9.8862	9.6452	8.8700
.5625	9.7037	9.5063	8.8712
.6875	9.9745	9.7221	8.9112
.8125	9.8634	9.6547	8.9824
.9375	9.9778	9.7378	8.9621
.0625	9.7130	9.5138	8.8673
.1875	9.7612	9.5457	8.8550
.3125	9.5838	9.3905	8.7721
.4375	9.5684	9.3843	8.7954
.5625	9.4714	9.2833	8.6812
.6875	9.6603	9.4443	8.7542
.8125	9.4519	9.2590	8.6421
.9375	9.5927	9.3573	8.6008

INITIAL SAMPLES

MI	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
36.3	0	4	5	1.040

WEIGHT IN GRAMS

X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
.0625	9.6121	9.3936	8.7858
.1875	9.5271	9.2797	8.5983
.3125	9.3520	9.1313	8.5228
.4375	9.7315	9.4965	8.8482
.5625	9.4080	9.2172	8.6920
.6875	9.7004	9.4442	8.7448
.8125	9.6200	9.3953	8.7808
.9375	10.2321	9.9765	9.2781
.0625	9.5670	9.3584	8.7774
.1875	9.5537	9.3059	8.6274
.3125	8.8979	8.7259	8.2483
.4375	9.6984	9.4400	8.7275
.5625	9.5928	9.3839	8.8078
.6875	9.6269	9.4025	8.7829
.8125	9.4027	9.2216	8.7215
.9375	9.7873	9.5255	8.8058
.0625	9.2812	9.0831	8.5300
.1875	9.4214	9.1646	8.4558
.3125	8.8252	8.6446	8.1482
.4375	9.1080	8.9096	8.3666
.5625	9.0546	8.8630	8.3392
.6875	9.3259	9.0927	8.4522
.8125	9.3707	9.1541	8.5578
.9375	9.3678	9.1226	8.4444

INITIAL SAMPLES

MI	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
29.6	0	5	10	.240

WEIGHT IN GRAMS

X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
.0625	9.9745	9.7490	8.9900
.1875	10.0376	9.7958	8.9842
.3125	9.8115	9.6175	8.9631
.4375	9.9640	9.7261	8.9230
.5625	9.6754	9.4807	8.8220
.6875	9.8840	9.6366	8.8041
.8125	9.7195	9.4989	8.7561
.9375	9.7712	9.5276	8.7106
.0625	9.3897	9.2061	8.5863
.1875	9.6655	9.4126	8.5555
.3125	9.4895	9.2765	8.5541
.4375	9.6995	9.4347	8.5398
.5625	9.4800	9.2652	8.5362
.6875	9.4990	9.2600	8.4503
.8125	9.2242	8.9984	8.2368
.9375	9.2611	9.0110	8.1584
.0625	9.7143	9.5127	8.8344
.1875	9.7997	9.5943	8.9000
.3125	9.6999	9.5145	8.8875
.4375	9.8987	9.6746	8.9148
.5625	9.6186	9.4470	8.8657
.6875	9.7132	9.5158	8.8488
.8125	9.6798	9.4914	8.8562
.9375	9.8165	9.5823	8.7938

INITIAL SAMPLES

MI	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
29.8	0	5	10	.700

WEIGHT IN GRAMS

X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
.0625	9.6152	9.4525	8.9000
.1875	9.8651	9.6468	8.9155
.3125	9.6441	9.4776	8.9169
.4375	9.8711	9.6534	8.9238
.5625	9.6047	9.4577	8.9636
.6875	9.9047	9.6908	8.9852
.8125	9.7567	9.5798	8.9900
.9375	9.8630	9.6635	8.9963
.0625	9.8548	9.6898	9.1310
.1875	10.1266	9.9053	9.1634
.3125	9.9489	9.7697	9.1689
.4375	10.0390	9.8431	9.1846
.5625	9.9115	9.7454	9.1883
.6875	10.1891	9.9627	9.2058
.8125	9.9851	9.8060	9.2060
.9375	10.2345	10.0106	9.2524
.0625	10.1503	9.9485	9.2717
.1875	10.0678	9.8897	9.2954
.3125	10.0361	9.8734	9.3310
.4375	10.2580	10.0500	9.3498
.5625	10.1885	9.9997	9.3658
.6875	10.3394	10.1273	9.4169
.8125	10.3394	10.1273	9.4169
.9375	10.5320	10.2959	9.4967

APPENDIX E

RAW DATA FOR DRIED SAMPLES

The eight headings under DRIED SAMPLES on each page of Appendix E represent:

MI = M_i = initial moisture content, % dry basis

TO = T_o, ^oR = absolute temperature at open end of drying samples

TL = T_L, ^oR = absolute temperature at sealed end of drying samples

PO/PS = P_o/P_s = relative humidity at open end of drying samples

HOURS ELAPSED = elapsed drying time in hours

TEST NO = number of test in experimental schedule

PI TERM NO = number of Pi term varied in test

PI TERM LEVEL = level of Pi term varied in test

DRIED SAMPLES

MI	TOR	TLR	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
25.4	541	541	.50	30	1	8	25.400

			WEIGHT IN GRAMS		
	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	9.0748	9.0162	8.6208
TUBE	13.2390	.09375	8.9635	8.8931	8.5292
		.15625	9.1402	9.0548	8.6973
TUBE PLUS		.21875	9.1536	9.0592	8.6814
WET CORN		.31250	9.5033	9.3427	8.7137
MEAL	20.5750	.43750	9.6542	9.4651	8.7335
		.56250	9.1124	9.0113	8.6131
TUBE PLUS		.68750	9.6211	9.4303	8.6906
DRIED CORN		.81250	9.5600	9.4123	8.8405
MEAL	20.5093	.93750	9.3527	9.1987	8.6053
		.03125	9.1999	9.1417	8.7445
TUBE	14.0421	.09375	9.3757	9.2685	8.7300
		.15625	9.1889	9.1104	8.7855
TUBE PLUS		.21875	9.2549	9.1522	8.7430
WET CORN		.31250	9.6437	9.4654	8.7664
MEAL	22.2003	.43750	9.7374	9.4955	8.5543
		.56250	9.1769	9.0218	8.4176
TUBE PLUS		.68750	9.8708	9.6671	8.8724
DRIED CORN		.81250	9.5384	9.3810	8.7678
MEAL	22.1266	.93750	9.5179	9.3497	8.6923
		.03125	9.1013	9.0521	8.7065
TUBE	14.3124	.09375	9.2366	9.1656	8.7924
		.15625	8.9679	8.8989	8.6041
TUBE PLUS		.21875	9.1856	9.0646	8.5858
WET CORN		.31250	9.5022	9.3467	8.7374
MEAL	22.6682	.43750	9.5291	9.3410	8.6099
		.56250	9.3563	9.2107	8.6476
TUBE PLUS		.68750	9.5578	9.3729	8.6577
DRIED CORN		.81250	9.4745	9.3116	8.6814
MEAL	22.6095	.93750	9.3878	9.2398	8.6650

DRIED SAMPLES

MI	TOR	TLR	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
29.8	541	541	.50	30	1	8	29.800

WEIGHT IN GRAMS

	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	9.0163	8.9570	8.5716
TUBE	13.8625	.09375	9.1426	9.0603	8.6775
		.15625	9.1532	9.0454	8.6662
TUBE PLUS		.21875	8.9252	8.8158	8.4403
WET CORN		.31250	9.5916	9.3869	8.6953
MEAL	21.7465	.43750	9.1200	8.9083	8.2042
		.56250	9.4017	9.2116	8.5787
TUBE PLUS		.68750	9.3336	9.1011	8.3244
DRIED CORN		.81250	9.2718	9.0865	8.4671
MEAL	21.6569	.93750	9.3317	9.1469	8.5325
		.03125	9.1992	9.1466	8.7930
TUBE	13.2432	.09375	9.1364	9.0524	8.6640
		.15625	9.3104	9.2111	8.8644
TUBE PLUS		.21875	9.4763	9.3493	8.9137
WET CORN		.31250	9.6110	9.4382	8.8549
MEAL	20.7847	.43750	9.9398	9.6886	8.8469
		.56250	9.6460	9.4714	8.8866
TUBE PLUS		.68750	9.8569	9.6367	8.8990
DRIED CORN		.81250	9.5489	9.3845	8.8332
MEAL	20.7004	.93750	9.6314	9.4497	8.8389
		.03125	9.9168	9.8547	9.4405
TUBE	13.1010	.09375	9.6541	9.5674	9.1879
		.15625	9.8038	9.7040	9.3570
TUBE PLUS		.21875	9.9116	9.7905	9.3818
WET CORN		.31250	9.9790	9.7856	9.1308
MEAL	20.8919	.43750	10.2895	10.0319	9.1674
		.56250	10.1306	9.9373	9.2933
TUBE PLUS		.68750	10.3367	10.0760	9.2040
DRIED CORN		.81250	9.3575	9.2196	8.7554
MEAL	20.8081	.93750	9.4478	9.2672	8.6618

DRIED SAMPLES

MI	TOR	TLR	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
35.0	541	541	.50	30	1	8	35.000

WEIGHT IN GRAMS

	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	9.0103	8.9597	8.6340
TUBE	12.9043	.09375	9.1392	9.0534	8.7087
		.15625	9.1552	9.0504	8.7441
TUBE PLUS		.21875	9.2320	9.1070	8.7456
WET CORN		.31250	9.4900	9.3097	8.7952
MEAL	20.1222	.43750	10.6403	10.3882	9.6758
		.56250	10.3006	10.1142	9.5880
TUBE PLUS		.68750	10.3535	10.0921	9.3583
DRIED CORN		.81250	10.4436	10.2411	9.6719
MEAL	20.0230	.93750	10.0165	9.8077	9.2276
		.03125	8.9902	8.9333	8.5634
TUBE	13.1307	.09375	8.7708	8.7023	8.4138
		.15625	9.0983	8.9673	8.5834
TUBE PLUS		.21875	9.0080	8.8844	8.5317
WET CORN		.31250	9.8735	9.6713	9.0922
MEAL	20.4271	.43750	9.9463	9.7113	9.0429
		.56250	10.0527	9.8186	9.1613
TUBE PLUS		.68750	9.8745	9.6605	9.0537
DRIED CORN		.81250	10.0582	9.8394	9.2215
MEAL	20.3237	.93750	9.8081	9.6117	9.0530
		.03125	8.8981	8.8524	8.5357
TUBE	13.7520	.09375	9.4432	9.3557	8.9835
		.15625	8.6555	8.5481	8.2362
TUBE PLUS		.21875	9.1055	8.9630	8.5546
WET CORN		.31250	9.2037	9.0098	8.4492
MEAL	21.1291	.43750	9.1562	8.8961	8.1577
		.56250	9.5141	9.2783	8.6089
TUBE PLUS		.68750	9.5636	9.3096	8.5849
DRIED CORN		.81250	10.0662	9.8844	9.3694
MEAL	21.0303	.93750	10.4045	10.2052	9.6309

DRIED SAMPLES

MI	TOR	TLR	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
30.1	541	541	.50	12	2	9	8.370

WEIGHT IN GRAMS

	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	9.1077	9.0442	8.6659
TUBE	14.6477	.09375	9.1372	9.0328	8.6584
		.15625	9.0236	8.9373	8.6487
TUBE PLUS		.21875	9.1898	9.0573	8.6108
WET CORN		.31250	9.4655	9.2850	8.6823
MEAL	22.2192	.43750	9.7123	9.4855	8.7378
		.56250	9.3271	9.1554	8.5863
TUBE PLUS		.68750	9.5383	9.3203	8.6045
DRIED CORN		.81250	9.6009	9.3925	8.7068
MEAL	22.1640	.93750	9.7215	9.5053	8.7929
		.03125	9.1432	9.0774	8.6819
TUBE	13.8393	.09375	9.1392	9.0238	8.6081
		.15625	9.2926	9.1898	8.8411
TUBE PLUS		.21875	9.1202	9.0236	8.6910
WET CORN		.31250	9.4417	9.2520	8.6138
MEAL	21.6823	.43750	9.8097	9.5608	8.7342
		.56250	9.5449	9.3538	8.7150
TUBE PLUS		.68750	9.7190	9.4826	8.6977
DRIED CORN		.81250	9.3273	9.1440	8.5292
MEAL	21.6233	.93750	9.5635	9.3491	8.6208

DRIED SAMPLES

MI	TOR	TLR	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
30.1	541	541	.50	24	2	9	16.740

			WEIGHT IN GRAMS		
	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	9.5638	9.5001	9.1031
TUBE	14.5644	.09375	9.4268	9.3536	9.0437
		.15625	9.7930	9.7030	9.3931
TUBE PLUS		.21875	9.6820	9.5629	9.1670
WET CORN		.31250	10.1117	9.9598	9.4607
MEAL	21.9802	.43750	10.0981	9.8806	9.1722
		.56250	10.2743	10.0907	9.4920
TUBE PLUS		.68750	10.1956	9.9635	9.2100
DRIED CORN		.81250	10.0581	9.8494	9.1671
MEAL	21.9014	.93750	10.0760	9.8788	9.2305
		.03125	9.3591	9.2804	8.7952
TUBE	14.0149	.09375	9.1384	9.0628	8.7453
		.15625	9.1839	9.0854	8.7441
TUBE PLUS		.21875	9.3291	9.1871	8.7087
WET CORN		.31250	9.4257	9.2431	8.6340
MEAL	22.3738	.43750	9.4949	9.2722	8.5317
		.56250	9.4444	9.2403	8.5636
TUBE PLUS		.68750	9.4299	9.1945	8.4138
DRIED CORN		.81250	9.5929	9.3598	8.5836
MEAL	22.2872	.93750	9.5346	9.3104	8.5597
		.03125	9.6056	9.5548	9.2282
TUBE	14.3524	.09375	10.2578	10.1456	9.6719
		.15625	9.6761	9.6034	9.3587
TUBE PLUS		.21875	9.9515	9.8690	9.5880
WET CORN		.31250	10.3975	10.2307	9.6765
MEAL	21.7908	.43750	10.1968	9.9691	9.2215
		.56250	9.8103	9.6343	9.0532
TUBE PLUS		.68750	10.0000	9.7802	9.0542
DRIED CORN		.81250	10.0328	9.8290	9.1616
MEAL	21.7152	.93750	10.0979	9.8652	9.0922

DRIED SAMPLES

MI	TOR	TLR	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
30.1	541	541	.50	36	2	9	25.110

WEIGHT IN GRAMS

	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	8.9739	8.9159	8.5331
TUBE	13.2759	.09375	8.8951	8.8220	8.4676
		.15625	8.7784	8.6780	8.3249
TUBE PLUS		.21875	8.6830	8.5719	8.2046
WET CORN		.31250	9.3470	9.1660	8.5790
MEAL	20.9820	.43750	9.6410	9.4192	8.6955
		.56250	9.3816	9.1597	8.4405
TUBE PLUS		.68750	9.7189	9.4702	8.6662
DRIED CORN		.81250	9.5934	9.3778	8.6775
MEAL	20.8821	.93750	9.5094	9.2904	8.5716
		.03125	9.5578	9.5007	9.1308
TUBE	14.5784	.09375	9.5910	9.5191	9.1681
		.15625	9.6335	9.5356	9.1885
TUBE PLUS		.21875	9.6383	9.5379	9.2047
WET CORN		.31250	10.0539	9.8760	9.2941
MEAL	22.2333	.43750	10.2895	10.0707	9.3572
		.56250	10.3514	10.1208	9.3700
TUBE PLUS		.68750	10.1734	9.9877	9.3822
DRIED CORN		.81250	10.3294	10.1210	9.4412
MEAL	22.1349	.93750	10.6549	10.4154	9.6315
		.03125	9.1165	9.0603	8.6935
TUBE	15.1533	.09375	9.3050	9.2058	8.7455
		.15625	9.0446	8.9742	8.7303
TUBE PLUS		.21875	9.4163	9.2695	8.7858
WET CORN		.31250	9.4112	9.2552	8.7435
MEAL	22.8931	.43750	9.5775	9.3367	8.5562
		.56250	9.5315	9.3516	8.7669
TUBE PLUS		.68750	9.4221	9.1859	8.4186
DRIED CORN		.81250	9.6770	9.4627	8.7686
MEAL	22.7922	.93750	9.8709	9.6355	8.8734

DRIED SAMPLES

MI	TO R	TL R	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
30.1	541	541	.50	48	2	9	33.480

			WEIGHT IN GRAMS		
	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	9.2741	9.2168	8.8395
TUBE	14.9129	.09375	9.0853	9.0180	8.6640
		.15625	9.2100	9.1257	8.7933
TUBE PLUS		.21875	9.4076	9.2799	8.8555
WET CORN		.31250	9.8026	9.5780	8.8473
MEAL	22.7624	.43750	9.8440	9.6129	8.8644
		.56250	9.7752	9.5716	8.9141
TUBE PLUS		.68750	9.8660	9.6333	8.8866
DRIED CORN		.81250	9.8425	9.6195	8.8995
MEAL	22.6436	.93750	9.8210	9.5887	8.8348
		.03125	9.1436	9.0761	8.6386
TUBE	15.0808	.09375	9.0217	8.9616	8.6621
		.15625	9.1208	9.0377	8.7106
TUBE PLUS		.21875	9.0508	8.9821	8.7559
WET CORN		.31250	9.5866	9.4044	8.8038
MEAL	22.5069	.43750	9.6904	9.4851	8.8214
		.56250	9.8088	9.6000	8.9225
TUBE PLUS		.68750	9.8830	9.6641	8.9624
DRIED CORN		.81250	9.8760	9.6648	8.9835
MEAL	22.3897	.93750	9.9466	9.7205	8.9887
		.03125	8.5804	8.5254	8.1577
TUBE	14.9171	.09375	8.6520	8.5852	8.2362
		.15625	8.8314	8.7547	8.4528
TUBE PLUS		.21875	9.0362	8.9188	8.5357
WET CORN		.31250	9.3549	9.1624	8.5393
MEAL	22.4202	.43750	9.4283	9.2217	8.5531
		.56250	9.4245	9.2186	8.5555
TUBE PLUS		.68750	9.5892	9.3504	8.5855
DRIED CORN		.81250	9.6391	9.3991	8.6224
MEAL	22.3027	.93750	9.4719	9.2690	8.6089

DRIED SAMPLES

MI	TO R	TL R	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
29.9	541	560	.50	30	4	5	.966

WEIGHT IN GRAMS

	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	9.1046	9.0514	8.7107
TUBE	13.9718	.09375	9.2271	9.1489	8.7870
		.15625	9.0302	8.9189	8.5373
TUBE PLUS		.21875	9.0017	8.8996	8.5564
WET CORN		.31250	9.4595	9.2978	8.7490
MEAL	21.2521	.43750	9.8169	9.5757	8.7665
		.56250	9.5710	9.3803	8.7415
TUBE PLUS		.68750	9.6276	9.4200	8.7374
DRIED CORN		.81250	9.5728	9.3780	8.7359
MEAL	21.1627	.93750	9.5626	9.3848	8.7306
		.03125	10.0866	10.0247	9.6326
TUBE	14.0568	.09375	9.8210	9.7307	9.3254
		.15625	9.7464	9.6552	9.3275
TUBE PLUS		.21875	9.9316	9.8204	9.4421
WET CORN		.31250	10.2398	10.0478	9.3975
MEAL	21.6803	.43750	10.1861	9.9918	9.3458
		.56250	10.3111	10.0940	9.3595
TUBE PLUS		.68750	10.2867	10.0744	9.3732
DRIED CORN		.81250	10.3291	10.1096	9.3785
MEAL	21.5839	.93750	10.1599	9.9912	9.3854
		.03125	9.1770	9.1103	8.6942
TUBE	13.9980	.09375	9.0946	9.0192	8.6788
		.15625	9.0547	8.9707	8.6688
TUBE PLUS		.21875	9.1711	9.0493	8.6262
WET CORN		.31250	9.3196	9.1533	8.5876
MEAL	21.3822	.43750	9.5586	9.3310	8.5691
		.56250	9.4272	9.2259	8.5548
TUBE PLUS		.68750	9.4404	9.2320	8.5412
DRIED CORN		.81250	9.3529	9.1570	8.5054
MEAL	21.2884	.93750	9.2959	9.1156	8.4683

DRIED SAMPLES

MI	TOR	TLR	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
26.5	541	520	.50	30	4	5	1.040

	WEIGHT IN GRAMS	X/L	WEIGHT IN GRAMS: CONTAINER PLUS WET CORN MEAL	WEIGHT IN GRAMS: CONTAINER PLUS DRY CORN MEAL	WEIGHT IN GRAMS: CONTAINER
		.03125	9.4655	9.3975	8.9529
TUBE	14.4946	.09375	9.4067	9.3394	8.9924
		.15625	9.5085	9.4040	8.9736
TUBE PLUS		.21875	9.5677	9.4477	8.9857
WET CORN		.31250	9.5820	9.4085	8.7507
MEAL	23.1468	.43750	10.2422	9.9947	9.0590
		.56250	10.0066	9.8037	9.0354
TUBE PLUS		.68750	10.0786	9.8624	9.0404
DRIED CORN		.81250	10.0658	9.8735	9.1431
MEAL	23.0782	.93750	10.0908	9.8698	9.0560
		.03125	9.5754	9.5106	9.0932
TUBE	14.7884	.09375	9.5187	9.4396	9.0538
		.15625	9.4961	9.4074	9.0549
TUBE PLUS		.21875	9.7019	9.5897	9.1628
WET CORN		.31250	10.0339	9.8633	9.2219
MEAL	22.5393	.43750	10.1350	9.9450	9.2282
		.56250	10.2025	10.0271	9.3590
TUBE PLUS		.68750	10.5983	10.3891	9.5886
DRIED CORN		.81250	10.4830	10.3152	9.6724
MEAL	22.4775	.93750	10.5848	10.3916	9.6771
		.03125	9.0577	8.9846	8.5212
TUBE	13.1017	.09375	9.0830	8.9961	8.5886
		.15625	9.1876	9.1058	8.7825
TUBE PLUS		.21875	9.0136	8.9091	8.5245
WET CORN		.31250	9.3591	9.1975	8.5863
MEAL	21.0757	.43750	9.5854	9.3824	8.6112
		.56250	9.8757	9.7120	9.0883
TUBE PLUS		.68750	10.1488	9.9403	9.1502
DRIED CORN		.81250	10.1176	9.9398	9.2667
MEAL	21.0130	.93750	10.1477	9.9388	9.1710

DRIED SAMPLES

MI	TO R	TL R	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
31.1	541	520	.50	30	4	5	1.040

WEIGHT IN GRAMS

	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	9.5592	9.5004	9.1308
TUBE	12.6214	.09375	9.6437	9.5533	9.1681
		.15625	9.5782	9.4875	9.1883
TUBE PLUS		.21875	9.8168	9.6718	9.2051
WET CORN		.31250	10.0670	9.8824	9.2944
MEAL	20.0247	.43750	10.1940	9.9950	9.3578
		.56250	10.2245	10.0227	9.3704
TUBE PLUS		.68750	10.2988	10.0827	9.3828
DRIED CORN		.81250	10.1932	10.0157	9.4412
MEAL	19.9500	.93750	10.5348	10.3162	9.6315
		.03125	9.3148	9.2411	8.7956
TUBE	13.1169	.09375	9.1672	9.0831	8.7456
		.15625	9.2315	9.1177	8.7441
TUBE PLUS		.21875	9.1365	9.0362	8.7090
WET CORN		.31250	9.4801	9.2803	8.6345
MEAL	20.6155	.43750	9.4151	9.2064	8.5323
		.56250	9.4545	9.2449	8.5646
TUBE PLUS		.68750	9.3172	9.1056	8.4144
DRIED CORN		.81250	9.3215	9.1486	8.5841
MEAL	20.5437	.93750	9.5023	9.2762	8.5603
		.03125	8.9448	8.8644	8.3811
TUBE	13.2200	.09375	9.1951	9.1218	8.8239
		.15625	9.6196	9.5228	9.2050
TUBE PLUS		.21875	9.9106	9.7893	9.3946
WET CORN		.31250	10.0465	9.8566	9.2507
MEAL	20.9924	.43750	10.3514	10.1203	9.3750
		.56250	10.1967	9.9940	9.3431
TUBE PLUS		.68750	10.3078	10.0755	9.3227
DRIED CORN		.81250	10.1145	9.9270	9.3219
MEAL	20.9160	.93750	10.2411	10.0085	9.2700

DRIED SAMPLES

MI	TOR	TLR	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
36.3	541	520	.50	30	4	5	1.040

			WEIGHT IN GRAMS		
	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	9.5237	9.4567	9.0437
TUBE	13.1163	.09375	9.5505	9.4540	9.1026
		.15625	9.5497	9.4500	9.1671
TUBE PLUS		.21875	9.6946	9.5545	9.1667
WET CORN		.31250	10.0900	9.8445	9.1723
MEAL	20.9346	.43750	10.1582	9.9058	9.2108
		.56250	10.2324	9.9652	9.2315
TUBE PLUS		.68750	10.2631	10.0334	9.3931
DRIED CORN		.81250	10.1827	9.9907	9.4607
MEAL	20.8346	.93750	10.4812	10.2133	9.4925
		.03125	9.2868	9.2305	8.8734
TUBE	14.9823	.09375	9.2108	9.1253	8.7858
		.15625	9.1919	9.0836	8.7687
TUBE PLUS		.21875	9.2530	9.1240	8.7669
WET CORN		.31250	9.4715	9.2788	8.7457
MEAL	22.4589	.43750	9.6856	9.4340	8.7441
		.56250	9.6044	9.3722	8.7303
TUBE PLUS		.68750	9.4803	9.2724	8.6932
DRIED CORN		.81250	9.4079	9.1832	8.5562
MEAL	22.3595	.93750	9.3653	9.1096	8.4186
		.03125	8.6928	8.6243	8.2050
TUBE	14.0171	.09375	8.7338	8.6509	8.3249
		.15625	8.8934	8.7776	8.4410
TUBE PLUS		.21875	8.9736	8.8381	8.4679
WET CORN		.31250	9.4005	9.1680	8.5331
MEAL	21.9875	.43750	9.7028	9.4006	8.5727
		.56250	9.4269	9.2018	8.5795
TUBE PLUS		.68750	9.5988	9.3525	8.6671
DRIED CORN		.81250	9.3141	9.1467	8.6800
MEAL	21.8815	.93750	9.7393	9.4567	8.6972

DRIED SAMPLES

MI	TO R	TL R	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
29.6	541	541	.24	30	5	10	.240

	WEIGHT IN GRAMS	X/L	WEIGHT IN GRAMS: CONTAINER PLUS WET CORN MEAL	WEIGHT IN GRAMS: CONTAINER PLUS DRY CORN MEAL	WEIGHT IN GRAMS: CONTAINER
		.03125	9.5422	9.5033	9.1629
TUBE	.0000*	.09375	9.2175	9.1519	8.7613
		.15625	9.2539	9.1666	8.8156
TUBE PLUS		.21875	9.7183	9.5980	9.1843
WET CORN		.31250	10.1269	9.9444	9.3307
MEAL	.0000*	.43750	10.3542	10.1247	9.3496
		.56250	10.1959	10.0060	9.3655
TUBE PLUS		.68750	10.3276	10.1190	9.4163
DRIED CORN		.81250	10.1484	9.9817	9.4186
MEAL	.0000*	.93750	10.4987	10.2711	9.4965
		.03125	9.0666	9.0317	8.7007
TUBE	14.7638	.09375	9.2000	9.1453	8.7959
		.15625	9.1280	9.0555	8.7340
TUBE PLUS		.21875	9.3798	9.2613	8.8529
WET CORN		.31250	9.3407	9.1756	8.6100
MEAL	22.2668	.43750	9.7072	9.4599	8.6230
		.56250	9.3828	9.2134	8.6389
TUBE PLUS		.68750	9.5433	9.3429	8.6617
DRIED CORN		.81250	9.3811	9.2197	8.6642
MEAL	22.1363	.93750	9.8483	9.6200	8.8377
		.03125	8.8992	8.8663	8.5633
TUBE	14.5105	.09375	9.1613	9.0970	8.6983
		.15625	9.1995	9.1210	8.7943
TUBE PLUS		.21875	9.2347	9.1406	8.8147
WET CORN		.31250	9.5867	9.4169	8.8413
MEAL	22.0203	.43750	9.9018	9.6628	8.8560
		.56250	9.5989	9.4317	8.8653
TUBE PLUS		.68750	9.7391	9.5464	8.8954
DRIED CORN		.81250	9.6350	9.4723	8.9157
MEAL	21.8929	.93750	10.0245	9.7877	8.9951

* Weight recording lost

DRIED SAMPLES

MI	TOR	TLR	PO/PS	HOURS ELAPSED	TEST NO	PI NO	TERM LEVEL
29.8	541	541	.70	30	5	10	.700

	WEIGHT IN GRAMS				
	WEIGHT IN GRAMS	X/L	CONTAINER PLUS WET CORN MEAL	CONTAINER PLUS DRY CORN MEAL	CONTAINER
		.03125	8.5352	8.4770	8.1587
TUBE	14.4875	.09375	8.7009	8.6101	8.2370
		.15625	8.8810	8.7691	8.3823
TUBE PLUS		.21875	8.8837	8.7769	8.4146
WET CORN		.31250	9.2518	9.0685	8.4503
MEAL	21.9259	.43750	9.5130	9.2881	8.5333
		.56250	9.3877	9.1982	8.5603
TUBE PLUS		.68750	9.4600	9.2549	8.5633
DRIED CORN		.81250	9.5088	9.3456	8.7958
MEAL	21.8705	.93750	9.6740	9.4731	8.7949
		.03125	9.1742	9.1186	8.8073
TUBE	14.1708	.09375	9.1426	9.0808	8.8162
		.15625	9.2723	9.1712	8.8164
TUBE PLUS		.21875	9.3424	9.2239	8.8225
WET CORN		.31250	9.5327	9.3704	8.8248
MEAL	21.2290	.43750	9.7216	9.5174	8.8344
		.56250	9.5815	9.4102	8.8380
TUBE PLUS		.68750	9.7478	9.5393	8.8423
DRIED CORN		.81250	9.5927	9.4105	8.7965
MEAL	21.1750	.93750	9.7191	9.5093	8.8045
		.03125	9.2547	9.1942	8.8488
TUBE	13.4236	.09375	9.3391	9.2437	8.8539
		.15625	9.2895	9.1920	8.8565
TUBE PLUS		.21875	9.4270	9.2965	8.8575
WET CORN		.31250	9.6573	9.4745	8.8660
MEAL	21.4274	.43750	9.9761	9.7202	8.8662
		.56250	9.7097	9.5204	8.8880
TUBE PLUS		.68750	9.8135	9.6033	8.8971
DRIED CORN		.81250	9.6628	9.4547	8.7563
MEAL	21.3686	.93750	9.8013	9.5629	8.7616

VITA

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Doctor of Philosophy

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